Forschungsbericht 2023-21

Creating a Virtual Helicopter Cockpit with an Immersive Head-Mounted Display

Johannes Maria Ernst

Deutsches Zentrum für Luft- und Raumfahrt
Institut für Flugführung
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Eine eingeschränkte Außensicht — durch ungünstige Umweltbedingungen, luftfahrzeuginduziert oder einsatzspezifisch — stellt für Hubschrauberpiloten eine große Herausforderung dar, insbesondere bei Einsätzen in Boden- und Hindernisnähe. Motiviert durch die jüngsten technologischen Fortschritte bei kopfgetragenen Anzeigen, sogenannten "head-mounted displays" (HMD), untersucht diese Dissertation, wie solche modernen Anzeigegeräte die Einschränkungen bestehender Anzeigelösungen überwinden und dadurch das Situationsbewusstsein der Piloten verbessern und die Flugsicherheit erhöhen können.

Was diese Arbeit von der bisherigen Forschung unterscheidet, ist die explizite Berücksichtigung von nicht-durchsichtigen HMDs neben den etablierten durchsichtigen Geräten. Basierend auf einer ausführlichen Untersuchung aktueller HMD-Technologien und moderner Flugzeugsichtsysteme wird in der Dissertation ein konzeptioneller Rahmen für zukünftige Cockpitgenerationen entwickelt: das Virtual Cockpit Continuum. Es beschreibt verschiedene Stufen der Cockpit-Virtualisierung — vom konventionellen Cockpit über mehrere teilweise virtuelle Varianten bis hin zu einem vollständig virtuellen Cockpit. In einem teilvirtuellen Cockpit werden Teile der natürlichen Außensicht und das Cockpit selbst von computergenerierten HMD-Anzeigen überlagert. In einem vollständig virtuellen Cockpit werden die gesamte Sicht aus dem Fenster sowie die Cockpitinstrumentierung vollständig durch eine virtuelle HMD-Sicht ersetzt. Je nach Grad der Virtualisierung wird dies mit optisch transparenten HMDs, mit Video-Durchsicht-HMDs oder mit nicht-durchsichtigen HMDs umgesetzt.

Die Dissertation analysiert die Potenziale und Herausforderungen eines solchen Ansatzes und implementiert anschließend sowohl ein teil- als auch ein vollvirtuelles Cockpit für den Offshore-Einsatz von Hubschraubern. Vier Probandenstudien bestätigen das große Potenzial der entwickelten Implementierungen eines virtuellen Cockpits. Virtuelle Instrumente, die auf einem durchsichtigen HMD dargestellt werden, scheinen eine vielversprechende kurz- bis mittelfristige Lösung zu sein, die die "head-up, eyes-out"-Zeit der Piloten verlängern kann und die Schaffung eines aufgabenangepassten Cockpits fördert. Ein vollständig virtuelles Cockpit mit einer verbesserten exozentrischen Sicht konnte das räumliche Bewusstsein der Piloten und die Präzision des Schwebefluges bei Einsätzen in Hindernisnähe verbessern. Zusammenfassend empfiehlt der Autor, die Untersuchung dieser Ideen fortzusetzen, und erörtert ausführlich die Forschungsfragen, die es zu beantworten gilt.

Virtual cockpit, head-mounted display, mixed/virtual/augmented reality, degraded visual environment, helicopter offshore operations, synthetic/enhanced/combined vision system, human factors

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Degraded outside vision — through adverse environmental conditions, aircraft-induced, or operation-specific — poses a major challenge for helicopter pilots, especially during operations close to the ground and obstacles. Motivated by the recent technological advancements of head-mounted displays (HMD), this dissertation explores how such modern display devices can overcome the limitations of existing display solutions and thereby improve the pilots' situation awareness and increase flight safety.

What sets this work apart from existing research is that it explicitly considers non-see-through HMDs besides the established see-through devices. Based on an extensive review of current HMD technologies and state-of-the-art aircraft vision systems, the dissertation devises a conceptual framework for next-generation flight decks called the virtual cockpit continuum. It describes different degrees of cockpit virtualization — from a conventional flight deck via several partially virtual variants to a fully virtual cockpit. In a partially virtual cockpit, parts of the natural out-the-window view and the flight deck itself are augmented by computer-generated HMD symbology. In a fully virtual cockpit, the whole out-the-window view as well as the flight deck instruments are entirely replaced by a virtual view through the HMD. Depending on the level of virtualization, this is achieved with optical see-through, video-see-through, or non-see-through HMDs.

The dissertation analyzes the potentials and challenges of such an approach and then implements both a partially and a fully virtual cockpit for helicopter offshore operations. Four pilot-in-the-loop studies confirm the great potential of the developed virtual cockpit implementations. Virtual instruments presented on a see-through HMD appear to be a promising near-/mid-term solution that can increase “head-up, eyes-out” time and promotes the creation of a task-adaptable cockpit. A fully virtual cockpit with an enhanced exocentric view was found to improve the pilots' spatial awareness and hover precision in confined area operations. In summary, the author recommends to continue the exploration of this topic and provides a thorough discussion of research questions that need to be addressed.

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Diese Veröffentlichung wird gleichzeitig in der Berichtsreihe „NFL - Forschungsberichte“ geführt.

Diese Arbeit erscheint gleichzeitig als von der Fakultät für Maschinenbau der Technischen Universität Carolo-Wilhelmina zu Braunschweig zur Erlangung des akademischen Grades eines Doktor-Ingenieurs genehmigte Dissertation.

Creating a Virtual Helicopter Cockpit with an Immersive Head-Mounted Display

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Abstract

Degraded outside vision — through adverse environmental conditions, aircraft-induced, or operation-specific — poses a major challenge for helicopter pilots, especially during operations close to the ground and obstacles. Motivated by the recent technological advancements of head-mounted displays (HMD), this dissertation explores how such modern display devices can overcome the limitations of existing display solutions and thereby improve the pilots' situation awareness and increase flight safety. What sets this work apart from existing research is that it explicitly considers *non-see-through* HMDs besides the established see-through devices. Based on an extensive review of current HMD technologies and state-of-the-art aircraft vision systems, the dissertation devises a conceptual framework for next-generation flight decks called the *virtual cockpit continuum*. It describes different degrees of cockpit virtualization — from a conventional flight deck via several partially virtual variants to a fully virtual cockpit. In a partially virtual cockpit, parts of the natural out-the-window view and the flight deck itself are augmented by computer-generated HMD symbology. In a fully virtual cockpit, the whole out-the-window view as well as the flight deck instruments are entirely replaced by a virtual view through the HMD. Depending on the level of virtualization, this is achieved with optical see-through, video-see-through, or non-see-through HMDs. The dissertation analyzes the potentials and challenges of such an approach and then implements both a partially and a fully virtual cockpit for helicopter offshore operations. Four pilot-in-the-loop studies confirm the great potential of the developed virtual cockpit implementations. Virtual instruments presented on a see-through HMD appear to be a promising near-/mid-term solution that can increase "head-up, eyes-out" time and promotes the creation of a task-adaptable cockpit. A fully virtual cockpit with an enhanced exocentric view was found to improve the pilots' spatial awareness and hover precision in confined area operations. In summary, the author recommends to continue the exploration of this topic and provides a thorough discussion of research questions that need to be addressed.

Kurzzusammenfassung

Eine eingeschränkte Außensicht — durch ungünstige Umweltbedingungen, luftfahrzeuginduziert oder einsatzspezifisch — stellt für Hubschrauberpiloten eine große Herausforderung dar, insbesondere bei Einsätzen in Boden- und Hindernisnähe. Motiviert durch die jüngsten technologischen Fortschritte bei kopfgetragenen Anzeigen, sogenannten "head-mounted displays" (HMD), untersucht diese Dissertation, wie solche modernen Anzeigegeräte die Einschränkungen bestehender Anzeigelösungen überwinden und dadurch das Situationsbewusstsein der Piloten verbessern und die Flugsicherheit erhöhen können. Was diese Arbeit von der bisherigen Forschung unterscheidet, ist die explizite Berücksichtigung von nicht-durchsichtigen HMDs neben den etablierten durchsichtigen Geräten. Basierend auf einer ausführlichen Recherche zu aktuellen HMD-Technologien und Flugzeugsichtsystemen wird in der Dissertation ein konzeptioneller Rahmen für zukünftige Cockpitgenerationen entwickelt: das *Virtual Cockpit Continuum*. Es beschreibt verschiedene Stufen der Cockpit-Virtualisierung — vom konventionellen Cockpit über mehrere teilweise virtuelle Varianten bis hin zu einem vollständig virtuellen Cockpit. In einem teilvirtuellen Cockpit werden Teile der natürlichen Außensicht und das Cockpit selbst von computergenerierten HMD-Anzeigen überlagert. In einem vollständig virtuellen Cockpit werden die gesamte Sicht aus dem Fenster sowie die Cockpitinstrumentierung vollständig durch eine virtuelle HMD-Sicht ersetzt. Je nach Grad der Virtualisierung wird dies mit optisch transparenten HMDs, mit Video-Durchsicht-HMDs oder mit nicht-durchsichtigen HMDs umgesetzt. Die Dissertation analysiert die Potenziale und Herausforderungen eines solchen Ansatzes und implementiert anschließend sowohl ein teil- als auch ein vollvirtuelles Cockpit für den Offshore-Einsatz von Hubschraubern. Vier Probandenstudien bestätigen das große Potenzial der entwickelten Implementierungen eines virtuellen Cockpits. Virtuelle Instrumente, die auf einem durchsichtigen HMD dargestellt werden, scheinen eine vielversprechende kurz- bis mittelfristige Lösung zu sein, die die "head-up, eyes-out"-Zeit der

Piloten verlängern kann und die Schaffung eines aufgabenangepassten Cockpits fördert. Ein vollständig virtuelles Cockpit mit einer verbesserten exozentrischen Sicht konnte das räumliche Bewusstsein der Piloten und die Präzision des Schwebefluges bei Einsätzen in Hindernisnähe verbessern. Zusammenfassend empfiehlt der Autor, die Untersuchung dieser Ideen fortzusetzen, und erörtert ausführlich die Forschungsfragen, die es zu beantworten gilt.

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Contents

Chapter 1

Introduction[1]

Driven by new technology, the appearance of aircraft cockpits changed considerably over the years [271, 303]. The classic gauge instruments were replaced by wide-screen, flat-panel monitors. Even augmented reality (AR) — a technology originally known from science fiction movies — has long since become an everyday occurrence on modern flight decks, for example in the form of head-up displays. In recent years, head-worn AR and virtual reality (VR) displays have experienced a major boom, which results in enormous investments in research and development of the corresponding hardware. This dissertation develops, implements, and evaluates several flight guidance display concepts that demonstrate how these emerging technologies can contribute to making helicopter operations more efficient and safer.

1.1 Problem Statement

The famous aviation pioneer Igor Sikorsky once described the value of helicopters as follows [306]:

[1] Parts of this chapter have been published by the author in [77] and [72], © 2021 IEEE.

> If a man is in need of rescue, an airplane can come in and throw flowers on him, and that's just about all. But a direct lift aircraft could come in and save his life.

But why are rotorcraft so important for life-saving rescue and medical services in both the civil and the military sector? The reason for this lies in the unique characteristics of helicopters: They are able to take off and land vertically on unprepared sites without runway infrastructure. Further, they can hover and maneuver slowly in every direction, which allows the crew to hoist persons or goods if a landing is not possible. Besides search and rescue (SAR) and helicopter emergency medical services (HEMS), rotorcraft are often used to transport people or freight to remote areas like offshore installations or military battlefields. Also, aerial work, police, and special military operations are common examples of the many helicopter domains.

During all of these missions, the pilots perform very demanding maneuvers like confined area landings or hoist operations. Further, all described scenarios have in common that the helicopters are often operated in unknown and unprepared environments, close to the ground, in the vicinity of man-made and natural obstacles such as buildings, wires, or trees. Usually, the pilots perform these tasks by looking out of the window. They rely on various kinds of visual cues to estimate the attitude, position, and movement of their aircraft. However, if the visibility is poor or if important points of interest are not observable from the pilot's seat, such complex missions become very challenging and often not safely accomplishable.

Figure 1.1 illustrates what poor visibility means with regard to helicopter operations. The U. S. military definition of "degraded visual environment (DVE)" includes rotorcraft-induced brown-/whiteout as well as several types of adverse environmental conditions: night, fog, clouds, rain, snow, flat light, smog, smoke, and sand/dust [293]. This classic notion of DVE can be expanded to include two operation-specific cases. For certain tasks, the outside vision is restricted by the fuselage or structure of the own aircraft [21]. For example, the view of the desired landing spot and potential obstacles can be blocked by the instrument panel during certain phases of the approach, especially with large helicopters. Additionally, the pilot's eyes are often not in the best position to have a sight of the whole situation. For instance, pilots can hardly see what happens behind, above, or directly below their aircraft. Finally, even in the best environmental conditions, certain objects are barely visible for the

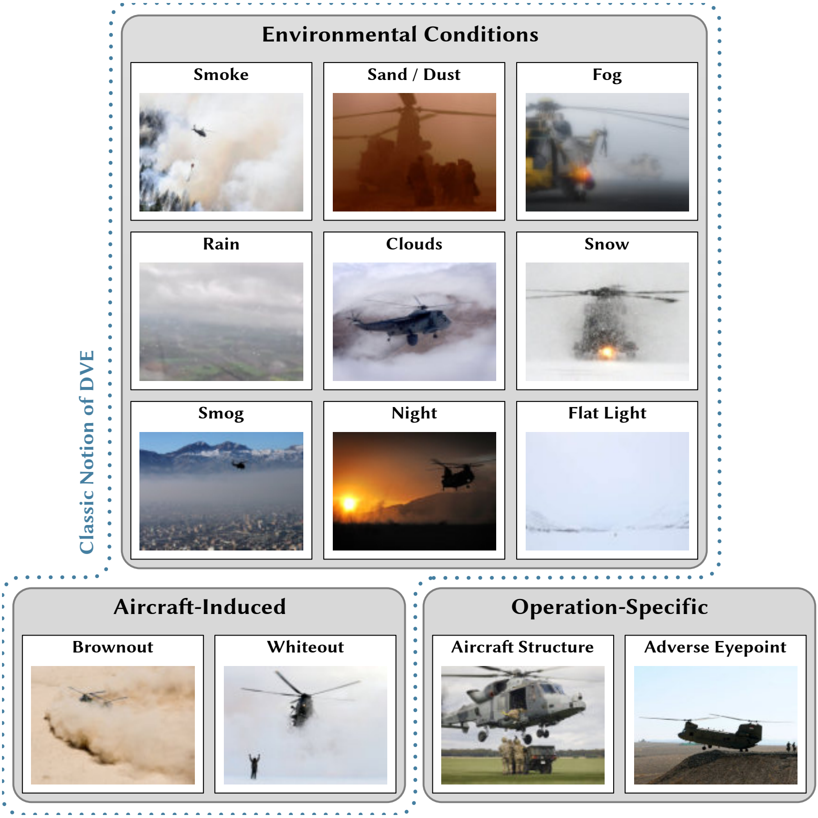


Figure 1.1 – Types of degraded visual environment (own illustration, expanded from [25, 293]). Image attributions: smoke: [a], sand/dust: [b], fog: [c], clouds: [d], snow: [e], smog: [f], night: [g], brownout: [h], whiteout: [i], aircraft structure: [j], adverse eye point: [k].

human eye because of their small size or their adverse visual properties. Power lines and wires, for example, are often indiscernible against the real-world background during low-level operations due to their small diameter.

Missing outside visual cues lead to increased pilot workload. Also, DVE often causes spatial disorientation and loss of situation awareness. As a result and as a precaution, many planned flights cannot be conducted. For example, HEMS, SAR, and police helicopters must often stay on ground and cannot complete their important missions when the weather conditions are too bad. Even worse, if a loss of visual references occurs during flight, this frequently leads to accidents like controlled flight into terrain (CFIT), crash landings, and object or wire strikes. These types of mishaps constitute a major portion of civil [84, 219, 327] and military accident statistics [116, 221].

As helicopters perform many important tasks in the military and civil sector, it is crucial to find solutions that improve safety and someday allow 24/7 operations regardless of visual conditions. In the future, this could — for instance — enable life-saving HEMS despite poor visibility. Additionally — from a military point of view — the ability to intentionally operate in DVE creates a battlefield advantage if the adversary lacks these capabilities. Once, the maxim of the U. S. military was to “own the night” by using superior technology. In recent years, this shifted from one particular case of DVE to a larger goal: “Own DVE” [25, 293].

1.2 State-of-the-Art Solutions

Each type of DVE poses individual challenges. This leads to a great variety of requirements for DVE mitigation systems. Thus, various solutions have been implemented — often with the emphasis on a subset of the described DVE types. Overall, current research and development efforts focus on three areas:

1. aircraft-mounted sensors and databases,
2. display and cueing systems,
3. advanced flight control and management systems.

Figure 1.2 illustrates that these three technologies do not stand alone as a solution but must work hand in hand to provide the pilots with the best possible assistance in such highly demanding situations. Various types of databases and sensors (e.g. lidar, radar, infrared) are applied to “see through” the DVE. The gathered data is then fused to generate an image or model of the surroundings, which is in many DVE conditions superior to what the pilots see with the naked eye [174, 272]. Finally, display systems present the processed information to the pilots in order to enhance their situation awareness [238, 326]. The displays replace the missing outside vision by providing cues for piloting and navigation [324]. Complementary to that, advanced flight control and management systems are integrated to simplify the manual flying task [117, 299]. This automation reduces the pilots' workload, frees mental capacity for other tasks, and ultimately avoids loss of control.

Each of the three technological areas presented in Fig. 1.2 has been realized in many different ways, leading to numerous available solutions. Basic systems only use one sensor type and one display to offer assistance for one specific DVE scenario. The most advanced systems integrate all described technologies to cover a wide range of DVE.

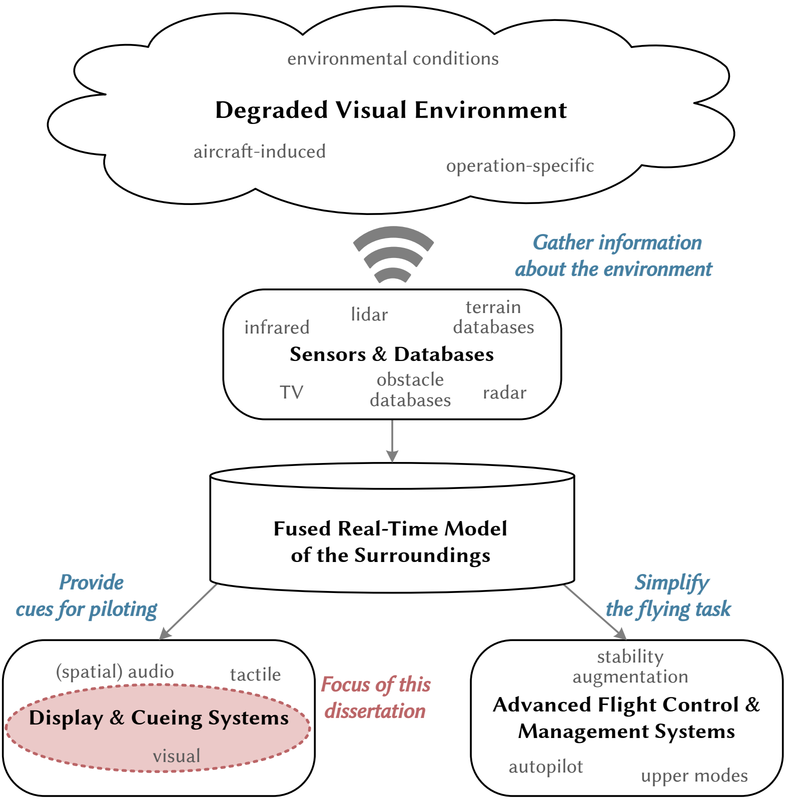


Figure 1.2 – DVE solution space and thesis focus (own figure, inspired by [220]).

Different types of DVE require different types of sensors. For instance, small, indiscernible obstacles during low-level flights can be sensed with Hensoldt's forward-looking SferiSense 500 lidar, which detects 5 mm thin wires in 725 m distance [212]. The restricted cockpit vision during low-speed, close-to-ground operations, on the other hand, is better mitigated with a 360° near-field radar sensor setup like Airbus' Rotorstrike Alerting System [332]. Such systems help to avoid main and tail rotor strikes by providing obstacle detection in areas that are hardly visible from the pilot's seat due to aircraft structure and adverse eye point. Often data fusion of several sensors and databases is required to generate a reasonable model of the environment [48, 106, 170, 214].

The challenge of the display and cueing systems is to present all available data to the pilot in a convenient way. In addition to the classic visual displays, the "display & cueing systems" referred to in Fig. 1.2 also include tactile and (spatial) audio cueing systems. Both are used to relieve the often saturated visual channel. All modalities can substitute or complement each other. A softstop on the collective axis can, for example, provide an intuitive haptic cue for engine limits, complementing the common visual torque protection gauge [35, 210]. Also, tactile seat pans, belts, and shoulder pads were tested as tactile cueing systems [201]. Spatial audio was found suitable for multi-directional threat and obstacle warnings in confined areas [112, 223].

Modern flight control systems transfer certain parts of the helicopter control task from the pilots to the machine. The available solutions range from basic stability augmentation systems to 4-axis autopilots with automatic hover hold, hands-off trajectory following, and autonomous landing capability [298, 299]. Advanced control augmentation systems also provide upper modes like *attitude command, attitude hold* or *translational rate command* [117]. In these control modes, the pilots do not directly steer the helicopter anymore — as they did with mechanically linked control systems. Instead, they command — for instance — a desired translational rate which is then realized by the digital control system moving the actuators. In summary, all these solutions stabilize the helicopter, reduce the attention required to control the aircraft, and free mental capacity to monitor the surroundings and avoid obstacles.

Probably the most extensive research and development program of a DVE mitigation system covering all mentioned technologies is conducted by the U. S. Army. Over the years they advanced their initial brownout display [292] to a cutting-edge assistance system with several aircraft-mounted sensors and sophisticated guidance algorithms [106, 293, 298].

1.3 Contribution of this Dissertation

This thesis aims to contribute to the current research on how to extend the operational envelope and how to enable safe helicopter operations in DVE. To do so, it includes state-of-the-art systems from all areas of the aforementioned DVE solution space and places particular focus on how to advance one specific part: visual display & cueing systems (see marking in Fig. 1.2).

1.3.1 Knowledge Gap and Motivation

As depicted in Fig. 1.3, state-of-the-art solutions use either a panel-mounted display (PMD) or a see-through head- or helmet-mounted display (HMD), also known as AR display. An example of the former is the Integrated Cueing Environment (ICE) by the U. S. Army [294–296], while the latter approach is — for instance — adopted by Münsterer et al. [213, 215, 326], Schmerwitz et al. [268], and Viertler et al. [324]. Both methods have shown their benefits in many studies. PMDs can use full-color, high-resolution flat panel screens to present information in many different ways. Even egocentric views with a field of view up to 360° have been implemented on such displays [207]. A see-through HMD offers a way to visually integrate information in the pilot's out-the-window view. Conformal display symbologies like tunnel-in-the-sky or obstacle cues have been found to increase performance and safety in several scenarios [238].

Still, both PMDs and AR-HMDs suffer from several limitations. With PMDs, pilots have to look down at the instrument panel and cannot keep their eyes out to stay aware of the situation. Further, a PMD can only show a scaled-down, 2-D projection of the 3-D environment, in which the user cannot intuitively look around; they "act as 2-D 'peep holes' into the 3-D world in which the pilot must operate" [107]. AR-HMDs allow symbology that is directly mapped onto the real world [190]. Nevertheless, the overlay of synthetic and real world often leads to problems [234]: Display clutter [325] as well as brightness and color perception issues are very common [123, 124].

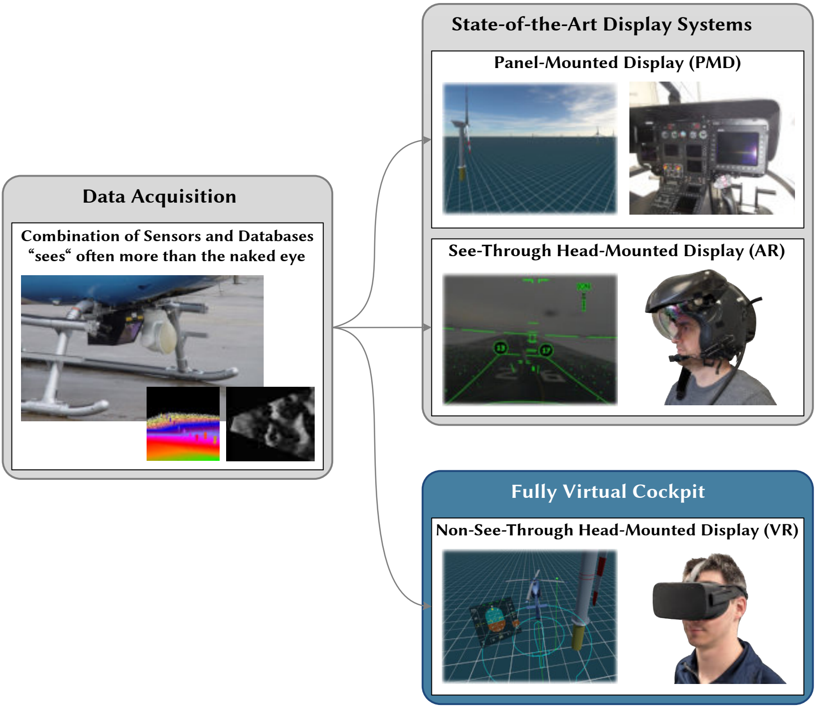


Figure 1.3 – Visual displays used by state-of-the-art systems and the fully virtual cockpit developed in this work. Both receive data about the surroundings from the same data sources (own figure [77]).

This raises the question of whether another display technology may have the potential to solve these problems. Especially the recent evolution of *non-see-through* VR-HMDs gives reason to ask if such displays could become an alternative or even a replacement for the established human-machine interfaces (HMI). Being able to show head-coupled symbology without the issues of AR overlays seems to be a promising feature that deserves further investigation — not least because today's VR-HMDs are more affordable, more comfortable to wear, and finally more capable than their bulky predecessors. They offer better resolution, greater field of view, lower latency, and more. On the other hand, the intentional blocking of the pilot's natural vision with an immersive HMD will certainly cause other issues to be considered carefully.

1.3.2 Research Objectives and Method

As stated above, the presented research is motivated by the limitations of current display solutions and the opportunities of advanced HMD technologies. The overall goal of the dissertation is:

> Advance current cockpit display solutions and develop HMI concepts for next-generation cockpits based on modern HMDs as principal flight guidance display.

To pursue this goal, the work was divided into two parts:

1. Concept development and theoretical assessment,
2. Implementation & experimental evaluation of exemplary applications.

The **first part** explores the following research questions (RQ):

RQ 1-A How can a VR-HMD — from a conceptual perspective — be used as a flight guidance instrument?

RQ 1-B What are the potentials & limitations of using such an immersive HMD compared to the established display systems (PMD, see-through HMD)?

This resulted in a concept called “virtual cockpit”. Figure 1.3 shows that the developed approach positions itself as an alternative display option that builds on the established data acquisition via sensors and databases. Using a fully immersive VR-HMD gives the HMI designer full control of what the pilot sees. One can create a virtual world that perfectly fits the pilot’s needs in the current situation. Nevertheless, this great freedom and flexibility come at the price that the pilot cannot directly see the real environment anymore. Thus, the author proposes — as sketched in Fig. 1.4 — that the image displayed on the VR-HMD should comprise two view domains: 1) an artificial view of the surroundings, and 2) a virtual cockpit environment and flight guidance symbology. However, it is very important to note at this point that neither the *virtual cockpit environment* nor the *external view* should be realized as an exact replication of its real-world counterpart. Instead, the imagined virtual cockpit wants to make use of its great opportunities and provide a view of the situation that overcomes current limitations.

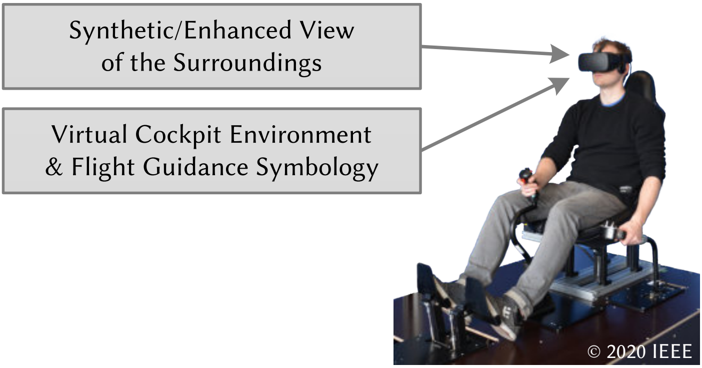


Figure 1.4 – The two view domains of a virtual cockpit which is based on an immersive head-mounted display (own illustration, image: [70, 72]).

The **second part** of the work investigates how this concept can be put into practice, answering the following questions:

RQ 2-A How can concrete implementations of a virtual cockpit look like?

RQ 2-B How do the novel symbologies influence the pilot's performance and situation awareness in selected DVE scenarios? What are the benefits and drawbacks?

The author implemented three different symbology concepts that show how a virtual cockpit can enable the pilots to safely fly their helicopter in DVE. The exemplary applications cover both view domains of the virtual cockpit stated in Fig. 1.4. The first work shows how contents that are conventionally displayed on PMDs can be transferred to flexible virtual cockpit instruments. The second and third symbology concepts demonstrate how to generate an artificial external view that is more than just a replication of the restricted natural out-the-window view. All implementations were evaluated with a total of four pilot-in-the-loop experiments in a flight simulator that the author specifically developed for this purpose.

1.3.3 Outline of the Thesis

Figure 1.5 illustrates the structure of the dissertation and sketches the relations between the chapters. The thesis comprises three major modules, represented by the gray boxes in the graph: The first part introduces the topic, provides basic knowledge, and situates the dissertation in the context of related research. The subsequent main body covers the development, the implementation, and the evaluation of the virtual cockpit by means of four flight simulator campaigns. The final section summarizes the findings and gives an outlook on future work.

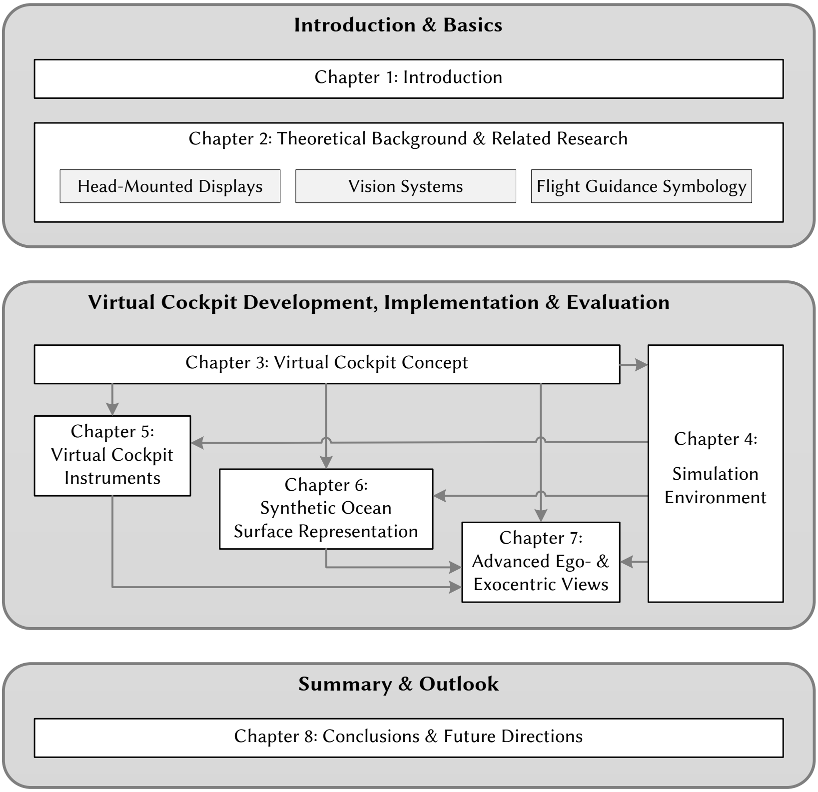


Figure 1.5 – Structure of the thesis (own illustration).

The introductory **Chapter 1** is followed by **Chapter 2** providing background information on relevant technologies, flight guidance displays, and operational concepts. It describes — for instance — the technical details of immersive virtual reality goggles and explains how they differ from augmented or mixed reality glasses. This is required as a basis to understand the HMD-based solutions, which are devised later in this work. Further, that chapter reviews state-of-the-art DVE mitigation systems in order to transfer existing knowledge to the newly developed virtual cockpit.

The following main body covers the work packages and research questions formulated above. **Chapter 3** describes the concept development of a virtual cockpit, answering research question 1-A. After a system description of this new approach, a thorough discussion of its advantages and drawbacks compared to state-of-the-art display systems is presented (RQ 1-B). Thereafter, **Chapter 4** explains how the theoretical plans are put into practice. It illustrates how the author implemented a simulation and evaluation environment to develop, test, and assess the novel symbology variants.

The following **Chapters 5–7** apply the developed ideas by showing three concrete implementations of a virtual cockpit. The conducted studies focus on three potentials of virtual cockpits identified in Chapter 3. They answer RQ 2-A and 2-B by presenting exemplary implementations and evaluating their benefits and limitations with four human-factors experiments. First, **Chapter 5** examines so-called virtual cockpit instruments — two-dimensional display areas, which are generated by the HMD. They can be placed anywhere in the virtual space around the pilot and thereby replace conventional PMDs. Second, **Chapter 6** shows the development of a synthetic external vision symbology that replaces the real out-the-window view and creates additional cues for helicopter offshore operations. Finally, **Chapter 7** discusses how a VR-HMD can be used to provide the pilots with non-conventional perspective views to enhance their spatial awareness in confined area operations. This includes, for instance, an exocentric view where the pilots see their ownship from a viewpoint behind and above the aircraft. As indicated by the arrows in Fig. 1.5, the final study applied the findings from the preceding experiments by incorporating a virtual cockpit instrument and a synthetic representation of the ocean surface.

The final **Chapter 8** recapitulates the main findings, draws conclusions, and recommends directions for future work on virtual cockpits.

1.3.4 Value, Scope, and Limitations

The literature provides very few findings relating to the application of non-see-through HMDs as primary flight guidance display. Until recently, it would have hardly been possible to actually realize such a concept because of the limited capabilities of early VR-HMDs. Besides VR-based simulators of conventional cockpits [e.g. 225, 264], only visionary descriptions of such future flight decks exist (see Sec. 2.1.5). Today, however, the latest technology advancements enable the author to further pursue what Furness [107] imagined as the "Super Cockpit" more than 30 years ago. Of course, the introduction of a new type of display technology and the complete restructuring of the HMI requires substantial effort including prototypical concept evaluations, actual system development, safety assessments, and many more. The contribution and value of this thesis is that it serves as a first step on the long path to the realization of this idea. It can be seen as exploratory research which provides a basis to decide if it is worth proceeding and going the next steps.

To explore the idea of a virtual cockpit, the author chose to develop exemplary applications for helicopter operations in offshore wind farms. The selected scenarios are good representatives of several types of challenging DVE conditions. Even though helicopter offshore operations seem to be a narrow field of application, the thesis will show that many concepts and findings can be transferred to a broader context, even beyond helicopter operations.

To fully focus on the development and assessment of the symbol sets, the work assumes to have sensors and databases that provide the required knowledge of the surroundings. Acquisition and processing of real sensor data are beyond the scope of this thesis. Instead, the author states which data is needed to realize each symbology and then assumes for the human factors evaluations that this information is available. When this time-consuming display development is completed, other researchers will have further advanced the capabilities of the data acquisition technologies as well. Such a parallel development approach is common practice for highly complex systems with long development cycles. After proving the general feasibility of the symbology concepts, it will be the next step to realize a fully integrated DVE mitigation system and evaluate the interaction of the sensor and the display side. This will also be the time to look at system failures like sensor or display malfunctions and discuss contingency procedures, which are not part of this work.

As the virtual cockpit concept targets future aircraft generations, the author supposes that these helicopters are equipped with a modern flight control system providing upper modes like *attitude command, attitude hold* or higher. Therefore, three of the four pilot-in-the-loop experiments are conducted with such advanced flight control modes.

Parts of the concept were implemented on consumer-grade hardware because current avionics do not have enough computing power and flight-certified, non-see-through HMDs are not available. Nevertheless, see-through HMDs, which use similar and related technologies, have already been manufactured as flight-certified devices. Thus, it is likely — from a technology perspective — that also non-see-through HMDs could be produced for the flight deck. The see-through virtual cockpit symbology presented in this thesis was evaluated with the flight-certified Elbit JedEye HMD.

This work mainly considers the output side of the HMI, that is the information flow from the cockpit systems to the pilot. The other direction, the interaction with virtual cockpit instruments, is only partly treated within this dissertation. At the current stage, the only means to communicate with the aircraft are the buttons on the cyclic and collective sticks, the pilot's line of sight, and, of course, the flight controls. Other input methods as well as the interaction with other crew members have to be treated by future research.

Chapter 2

Theoretical Background & Related Research

This chapter sets the theoretical framework and lays the foundation for the virtual cockpit developed in this work. It introduces relevant technologies like HMDs and vision systems and explains how HMDs can be used for next-generation simulators and future cockpits. Further, the chapter provides a review of related research on helicopter DVE mitigation systems. This includes a presentation of established approaches for the visualization of the external scene and flight guidance information on different types of displays (PMD, HMD). Finally, the usage of 3-D perspective views in flight guidance displays is discussed.

Readers who are familiar with these topics may only read the chapter summary in Sec. 2.5 or skip to Chapter 3, where the author introduces his concept of a virtual cockpit. All following chapters will refer back to this background chapter whenever an in-depth explanation of a topic may be helpful.

Please note that this chapter has been updated at the end of the author's work to reflect the latest progress in those fields. Several of the cited publications and technologies were not available when the author conducted his studies.

2.1 Head-Mounted Displays — Immersing the User in a Virtual World

The HMD is the central display device around which this dissertation creates a virtual cockpit. This section starts with an introduction to mixed and virtual environments in general and then describes different types of HMDs and explains their architecture, function, and current applications within aviation. Associated human factors in the cockpit context are discussed in Chapter 3.

2.1.1 Real, Mixed, and Virtual Environments[1]

Over the last decades, many terms have been established to describe the variety of new technologies in the field of mixed reality. However, terms like augmented and virtual reality are often used inconsistently. Sometimes they are even used interchangeably, although they do not describe the same type of system. Thus, this section gives an overview of common taxonomies and explains the terms and definitions that will be applied in this thesis. An in-depth review of terminology can be found in [20, 179].

A widely accepted taxonomy for **mixed reality (MR)** and related technologies was established by Milgram and Kishino [200]. As depicted in Fig. 2.1, their "reality-virtuality continuum" ranges from a purely real environment at the one end to a completely virtual, computer-generated environment on the opposite side. They argue that virtual and real environments should not be seen as mutually exclusive opposites but rather as "opposing poles of a continuous spectrum of possible combinations of real and virtual image content" [199]. The whole middle range between these poles is called MR. Depending on the rate of mixture between real and virtual elements, MR can be divided into its subgroups **augmented reality (AR)** and **augmented virtuality (AV)**. AR is then defined as any experience where the real environment is enhanced by virtual content. Analogously, AV refers to computer-generated environments augmented with real-world content.

The widely used term **virtual reality (VR)** is not explicitly mentioned in this continuum. Nevertheless, according to the common definition, this technology creates a fully synthetic environment, which implies that VR is a synonym

[1] Parts of this section have been published by the author in [75].

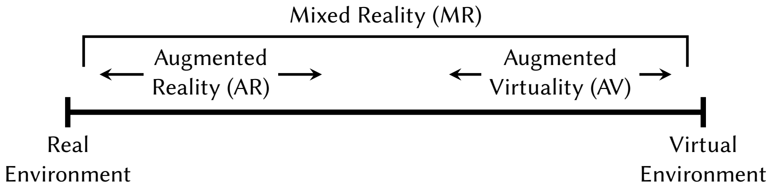


Figure 2.1 – Reality-virtuality continuum by Milgram and Kishino (adapted from [200], © 1994 IEICE).

for Milgram's "virtual environment" — the right extreme of the continuum. Sometimes, this is also called "virtuality" [179].

Milgram and Kishino explicitly state that their framework is not restricted to HMD-based experiences [200]. Even though today terms like AR and VR seem to be inextricably linked to transparent or immersive goggles, any other technology able to combine real and virtual images can be used. An example of a virtual environment is a computer game in which the users — sitting or standing in their living room — get completely immersed in a computer-generated world entirely disconnected from their real environment. Making them able to see and interact with their real hands or real gear in the virtual scene would shift this further left on the continuum to a certain degree of AV. By contrast, an example for AR is a head-up display (HUD) in the car, which leaves the users in their real environment and only adds some virtual content like route information to the natural view.

It is important to note that Milgram's framework — although it was constructed with visual experiences in mind — can easily be transferred to all types of technology which stimulate the user's perception with virtual inputs. For instance, playing music generates a virtual auditory experience that augments or replaces the user's perception of the sound originating from the real environment. The great challenge is to create experiences where virtual entities can be perceived with all senses: Depending on the scenario, the user must be able to see, touch, hear, and potentially even smell or taste a virtual object to create a holistic and natural experience of mixed or virtual environments.

Azuma [11] expands Milgram's definition of AR. He states that AR is "any system that has the following characteristics:

1. combines real and virtual
2. is interactive in real time
3. is registered in three dimensions"

In addition to Milgram's combination of real and virtual surroundings, this well-known definition requires the user to be able to actually interact with the virtual content. Finally, synthetic elements must be anchored in the real 3-D space. Similar to [200], Azuma does not restrict his notion to HMD-based experiences. Further, he explains that "augmented" also covers more human senses than visual perception only. Azuma also indicates that — even though most current work focuses on *adding* virtual elements — AR can also mean *removing* real elements.

Besides AR, VR, and MR, the initialism **XR** can be found in the literature. However, more than one definition for this term exists [179]. First, XR in the sense of "eXtended reality", a superset of Milgram's mixed reality that extrapolates beyond the "reality" pole [178]. Second, XR as "miXed reality", which is equal to Milgram's notion of MR [179]. Third, "cross-reality" as a specific subset of MR [231]. Finally, XR is sometimes used as generic term with 'X' being a placeholder for M(R), A(R), or V(R) [317]. This last definition is also used by this dissertation.

While Milgram's taxonomy describes technology that augments/mixes reality with virtuality, Mann [177] argues that technology can also modify reality. He calls this **mediated reality** and distinguishes between unintentionally and deliberately mediated reality [179]. The former covers cases where the used technology is not able to combine reality and virtuality without unintentionally modifying the real image. An example of the latter is Stratton's famous upside-down eyeglass used in 1896 to research the impact of inverted vision on the brain [289]. It also includes systems that diminish the reality, for instance, to protect the user from unwanted inputs (e.g. blinding sun rays). To account for this "mediality", Mann proposes a two-dimensional continuum [179]. Its x-axis exactly matches Milgram's definition of virtuality. The y-axis adds the mediality, i.e. the degree of reality modification.

2.1.2 Introduction to HMDs

The creation of the described mixed and virtual experiences requires sophisticated technology. Regarding the visual part, HMDs are often used for that.

2.1.2.1 History & Status Quo

Even though concepts and patents for helmet-mounted sights existed many decades ago [99, 243, 284], the actual history of HMDs began with Ivan Sutherland's "Sword of Damocles" [290]. This first HMD prototype was a bulky, heavy device with a head-tracking system hanging down from the ceiling — like the sword in the Greek anecdote.

(a) IHADSS of the Apache AH-64 helicopter [l]. **(b)** HMD of the F-35 Lightning II fighter [m]. **(c)** Microsoft HoloLens 2.

Figure 2.2 – Examples from the history of HMDs.

Thereafter, HMDs were mainly developed by the defense industry to support pilots and to enhance their combat capabilities [191]. Figure 2.2a shows a prominent example of that era: the Integrated Helmet and Display Sight System (IHADSS). It was the first fielded rotary-wing HMD[2] — developed in the 1970s and used on Apache AH-64 attack helicopters since the 1980s [19]. Over the past decades, several HMDs have been developed and fielded so that they become more and more common on today's military flight decks. For instance, the F-35 Lightning II uses its HMD as primary display, fully replacing the fixed HUD, which was common on the previous generation of fighter aircraft [34]. In civil cockpits, HMDs could not establish themselves so far — mostly due to different use cases, high costs, and insufficient wearing comfort. For further reading on the history of military HMDs, the author recommends the following sources: [168] (detailed list of military HMD programs), [99] (HMD history with focus on the role of Kaiser Electronics & Rockwell Collins), [19] (Honeywell's HMD developments), [30] (notable HMDs developed by BAE Systems), and [34] (status quo of HMDs in service and development).

[2] The first helmet-mounted sight was already used in the 1970s on the AH-1 Cobra helicopter, which had a mechanical linkage between the pilot's helmet and a turreted machine gun [99].

Regarding the commercial sector, a first boom of VR-HMDs was seen during the 1990s [193]. However, the technology was not capable enough for mass adoption at that time. It took until 2012 when Oculus' successful Kickstarter campaign [143] marked the start of a still ongoing era of massive investments in XR technologies [160]. These efforts led to a significantly improved generation of commercially available HMDs. Dozens of new devices[3] appeared during the last decade. A good example of the newest HMD generation is Microsoft's HoloLens 2, depicted in Fig. 2.2c. As one can already guess from the pictures, these devices offer considerably improved wearing comfort. Additionally, they are more capable and more affordable than their predecessors. Pushed by notable players like Meta/Facebook,[4] Microsoft, HTC, Varjo, HMDs seem to become a viable solution for specific commercial applications. Nevertheless, actual mass adoption of HMDs is still pending as it requires further technological improvements as well as rewarding use cases. Furthermore, it has to be noted that these devices do not meet the requirements of aviation systems like outdoor usage in high ambient light conditions (cf. Sec. 2.1.3).

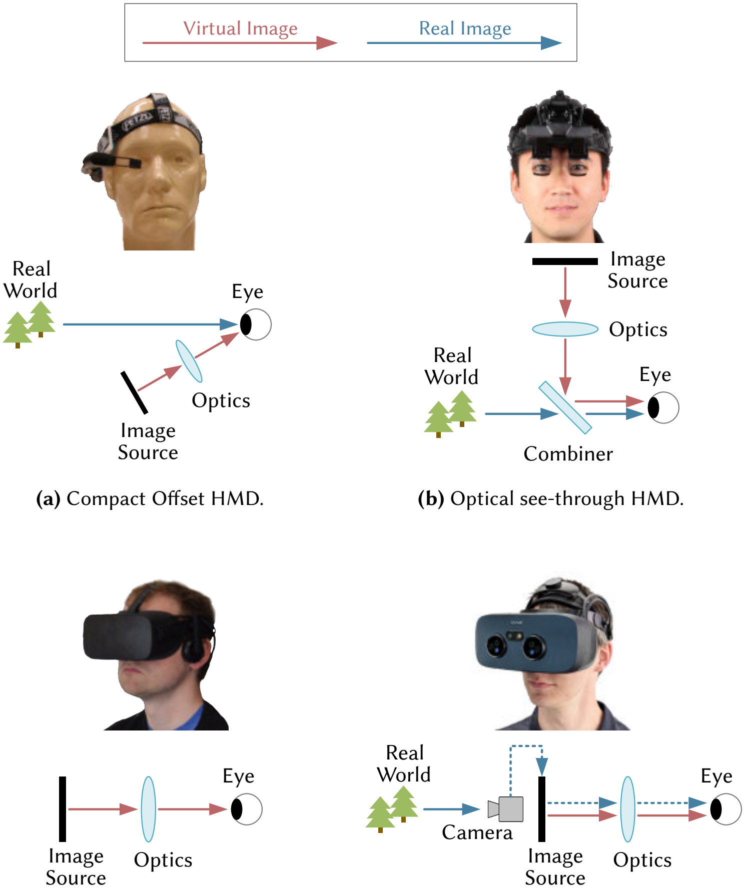
2.1.2.2 Terminology

The initialism HMD is used for both "helmet-mounted" and "head-mounted" displays [e.g. 195, 252]. The former indicates the military origins of HMDs — the display was attached to the pilot's helmet. Today, the term HMD is widely accepted for all sorts of "head-mounted displays" — regardless whether a helmet or a simple headband is used to attach the display to the user's head. Lately, also the universal "head-worn display" (HWD) became popular [7, 18].

2.1.2.3 Types[5]

Different types of HMDs are available to realize experiences in each area of the reality-virtuality continuum described in Fig. 2.1. All variants have in common that they feature an image source (e.g. a liquid crystal display (LCD)) and an optical system (lenses, waveguides, etc.), which deliver a computer-generated virtual image to the user's eyes (red arrows in Fig. 2.3). Depending on the type of device, this virtual information may somehow be mixed with a view of the real world (blue arrows).

[3] Lists of current devices are provided by [161, 193].
[4] Oculus was acquired by Facebook in 2014.
[5] Parts of this section have been published by the author in [75].



(a) Compact Offset HMD.

(b) Optical see-through HMD.

(c) Non-see-through HMD.

(d) Video-see-through HMD.

Figure 2.3 – Types of head-mounted displays [75] (classification adopted from [193], drawings inspired by [20, 193], images from [26, 340]).

Before explaining the different HMD types sketched in Fig. 2.3, it is important to understand that — parallel to the depicted classification — three basic HMD configurations are distinguished [194]: **Monocular** HMDs have one image source presenting information to only one eye. **Biocular** devices also have only one image source but the optics relay the (same) image to both eyes. Finally, **bi*n*ocular** configurations deliver stereo imagery as they integrate two image sources — one for each eye. The reasons to choose one design over the other are manifold, but in a nutshell, binocular HMDs offer superior properties like larger field of view, stereo images, fewer visual comfort issues (e.g. binocular rivalry) [191, 194]. However, this comes at the price of a higher rendering effort and a more complex optical setup, which adds weight and increases costs [300].

Compact Offset HMD Figure 2.3a shows what is called a compact offset or **"look around" HMD** [193]. With such a design, only a small part of the user's visual field is covered by the presented image. This small "inset" can provide information which is accessible with minimal effort (hands-free, only small eye movement required). As depicted, such HMDs are usually monocular.

Optical See-Through HMD The technically most complex system is the optical see-through HMD — often referred to as **augmented reality glasses**. The key part of such AR-HMDs is the beam splitter or "combiner", an optical element that reflects the virtual image from the display into the user's eyes and simultaneously lets the real world photons pass through (see Fig. 2.3b) [20]. Hence, the users see the virtual symbology superimposed onto their natural sight. The advantage of these **transparent HMDs** is that the real-world view is directly[6] seen, which keeps the natural feeling of presence in the real world [193]. The presentation of the virtual content has several issues mainly caused by the fact that the symbology can just be added on top of the real scene. Virtual elements cannot occlude real objects behind them, colors appear shifted due to the blending [123], and display luminance may be too low for high ambient light environments [322].

Non-See-Through HMD A non-see-through HMD — often called **VR goggle** — shows a virtual scene via a rather simple optical system: Mostly it is just a collimating lens in front of the display. As depicted in Figure 2.3c, VR-HMDs are typically designed as **immersive devices**, which means that a ski-goggle-like housing entirely blocks the view of the real environment. In

[6] The combiner can cause minor distortions and lowers the transmission of ambient light.

contrast to the see-through devices described above, VR-HMDs offer saturated colors and high contrast because the virtual image does not "compete" with the outside world [193].

Video-See-Through HMD The key feature of a video-see-through HMD are the two cameras that are integrated into the front of its housing. These provide a stereo[7] video stream of the surrounding reality, which is then shown on the display. A "mixed reality" can be created by blending the streamed imagery with virtual symbology. Figure 2.3d sketches the optical architecture, which is rather similar to VR-HMDs. As depicted, these devices — which are sometimes also called **electronic or digital see-through HMD** [e.g. 26, 161] — are usually (but not always [26]) designed as immersive goggles with no direct view of the real world.

Their big advantage is that embedding virtual content into the real-world video produces a considerably better visual experience than the superposition done by optical see-through HMDs. The ambient luminance can be controlled and virtual objects can actually occlude real elements, which results in a far more realistic appearance [161, 193]. Further, due to their simpler optical design, they can be significantly cheaper [161]. Nevertheless, they also have specific challenges: The motion-to-photon latency of the camera images must be very low to avoid disorientation and sickness symptoms [161, 193]. Moreover, camera and display resolution must be high enough and the distortions must be low enough to replicate the reality in sufficient quality [256]. As these challenges could not be met, most development programs before 2018 were discontinued [193]. Recently, however, as the required technology was improved, companies like Varjo [321] and SA Photonics [26] started to offer the next generation of video see-through devices. In 2020, Kress [161] even concluded that video-see-through HMDs have "the potential to become very popular in the coming years."

2.1.2.4 HMD as Part of a Visually Coupled System

If the display content should be aligned with the real 3-D space (not just a plain 2-D overlay), the HMD must be part of a "visually coupled system": As sketched in Fig. 2.4, this includes a head-tracker whose information is used to adapt the display content according to the user's viewing direction [300]. It

[7] The two cameras generate binocular disparity but no accommodation cues (see Sec. 3.3.1.3).

either triggers a render engine to re-render the scene from the current view angle or directly steers an imaging sensor (e.g. a gimbal-mounted IR-sensor on the helicopter [191]).[8] This is how HMDs are used in aviation. Different types and details of these vision systems are explained in Sec. 2.2.

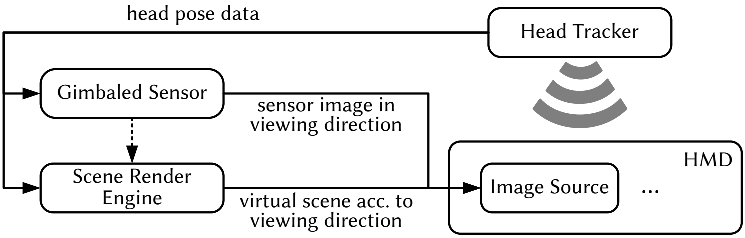


Figure 2.4 – The HMD as part of a visually coupled system[9] (own illustration).

2.1.2.5 Conclusions

There are two take-home messages from this section: First, several very different types of HMDs exist, each with its own advantages and limitations. Thus, the respective use case dictates which HMD design is most suitable. Second, the terminology is — at least partly — vague, inconsistent, and sometimes even misleading. For instance, using a VR-HMD does *not* inevitably imply that the created experience must be fully virtual, i.e. at the right extreme of Milgram's reality-virtuality continuum (see Fig. 2.1). Adding virtual representations of tracked/sensed real-world objects or imagery from a remote sensor (cf. visually coupled system) makes the user see a "mixed reality" — even though the HMD itself is an immersive, non-see-through device. Looking at this example and the blurred definitions, it is explainable why Microsoft calls all its HMDs "mixed reality goggles" [160], no matter if they are see-through or occluded.

In this dissertation, the author uses the following definition: "Virtual" means that the content is digitally created but it can still be a replication of the surrounding real world. How blurred the borders between real, mixed, and virtual are, will also be seen in the author's concept of a "virtual cockpit" presented in Sec. 3.1.

[8] A visually coupled system can either include a virtual scene generator, a sensor, or both.
[9] The head tracker can be external or integrated into the headset (details see Sec. 2.1.4.3).

2.1.3 HMD Design Goals

The development of an HMD is a complex and challenging task with several conflicting design goals. Since it is a personal device, worn on the head and closely interacting with the user's vision, the capabilities of the human dictate many design goals. Melzer and Moffit [189] even state that "the key to achieving success with HMDs is to put the user at the center of the design process." The blue ellipses in Fig. 2.5 show what Kress [160] identified as the "design pillars" of commercial and consumer HMDs: They must be comfortable to wear and the presented image must be pleasant to watch. Further, they should immerse the user in the virtual/mixed world while still being affordable.

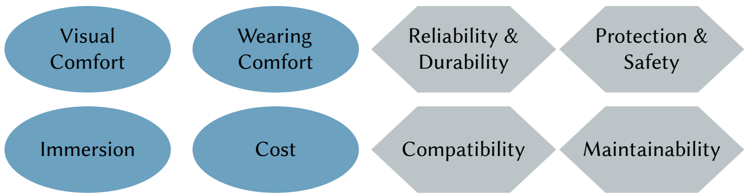


Figure 2.5 – HMD design pillars — Blue ellipses show key requirements for commercial & consumer HMDs [160]. The gray hexagons represent *additional* requirements for cockpit applications [189, 193, 322].

For usage in an aircraft cockpit (especially military), the immersion and cost goals may be less demanding or lower prioritized, but several additional requirements arise [189, 193, 322] (gray hexagons in Fig. 2.5): First, an HMD is a critical part of the cockpit, which means that it must fulfill the high quality and reliability criteria of the aviation authorities and also be durable enough for daily usage in demanding environments. Moreover, a pilot's HMD must be safe to wear in every possible situation (high-g maneuvers, emergency, crash protection). Finally, compatibility with existing avionics must be given and the maintenance effort must be reasonable.

The transfer of these overall design goals into specific system requirements leads to an ideal HMD architecture that meets the following[10] specifications simultaneously [161, 193–195, 322]:

- large field of view (FOV) with wide stereo overlap,

[10] The list does not claim to be exhaustive. Further details are found in the cited literature.

- large eyebox (to fit a wide range of interpupillary distances),
- large eye relief (to allow the user to wear glasses),
- high angular resolution,
- high & low luminance and contrast (for high & low light environments),
- low motion-to-photon latency,
- accurate & low-latency head-tracking and spatial environment mapping (to enable world-referenced virtual objects),
- full color images,
- correct depth cueing (vergence, accommodation, occlusion),
- small form factor, low weight, and center of gravity close to the head,
- wireless/untethered device (to allow free movement).

It is important to note that the relevance and the importance of the listed requirements depend strongly on the intended application [195]. A large FOV, for instance, is barely needed for displaying an aiming reticle or simple 2-D status information, but it is a basic requirement for complex 3-D conformal DVE symbology (see Sec. 2.3) [192]. Also, high luminance is only required if the device is actually used in a high ambient light environment.

Looking at current devices, it has to be stated that the ideal HMD as defined above has not been manufactured yet. In practice, several of the listed demands are contradictory, so the requirements must be prioritized and suitable design trade-offs must be found. Further, some of the ideal requirements may not be achievable at all. The subsequent section describes typical issues, presents state-of-the-art solutions addressing these problems, and finally states the challenges that researchers and manufacturers are currently working on.

2.1.4 Current Solutions & Technological Challenges

Manufacturing an HMD requires the development of various highly sophisticated hard- and software and a solid knowledge of the involved human factors. As mentioned before, this branch has seen major technological advancements over the last decade. This section summarizes key topics. For in-depth explanations, the reader is referred to the fundamental books by Melzer et al. [195], Rash et al. [252], and Velger [322] as well as the review of today's HMD technologies by Kress [161], which also form the basis of the following overview. In general, optical see-through optics are more complex and require more specific parts and techniques than occluded HMDs. Thus, several of the following explanations are only relevant for the former.

2.1.4.1 Optical Architectures

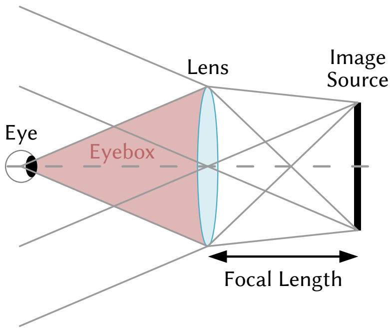
The optics of an HMD have three main tasks [191]:

1. **Magnify** — enlarge the image generated by the miniature display,
2. **Collimate** — make the virtual image appear farther away than the image source actually is, and
3. **Relay** — bring the image in front of the eyes.

The technologies used to achieve these vary widely, depending on whether the HMD is a non-/video-see-through or an optical see-through device.

Non- and Video-See-Through HMDs Devices with no direct see-through requirements typically use a **non-pupil-forming design**, also known as simple magnifier. As depicted in Fig. 2.6a, this is a compact, light, and rather simple architecture that often applies only a single lens per eye to magnify and collimate the image [300]. Due to its short optical path, it can hardly be used for other designs than the typical occluded HMD where the image source is placed directly in front of the user's eyes [193] (see Fig. 2.6b). The red area in Fig. 2.6a shows the eyebox, which is the space where the user's eye has to be placed to see the full image — outside of this it appears clipped.

Optical-See-Through HMDs HMDs with transparent combiner generally use **pupil-forming designs** as their longer, "foldable" optical path allows for better weight balancing and easier integration of the optical combiner [159, 194]. However, such architectures are also more complex and more expensive than a simple magnifier [300]. Figure 2.7a shows a ray trace of the IHADSS as an example for a long and folded optical design. Such bulky lens architectures have been used in many HMDs over the years [252]. In the course of the major technological advances during the last decade, conventional lens systems have been largely replaced by lighter and smaller waveguides in modern devices [161, 193]. As the name implies, pupil-forming designs create an exit pupil inside which the eye has to be positioned to see the image (red area in



(a) Ray trace of a non-pupil-forming design (adapted from [300]).

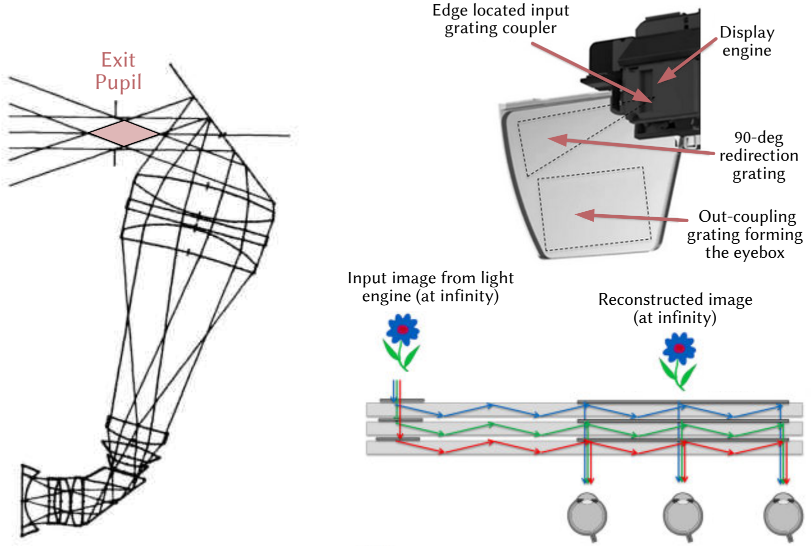
(b) Disassembled optical system of the Oculus Rift DK 2 (own image).

Figure 2.6 – Typical architecture of non- and video-see-through HMDs.

Fig. 2.7a). This is usually smaller than the eyebox of a simple magnifier [159]. Another disadvantage is that if the user's eye leaves this area, the image is not just clipped but not visible at all [194]. In summary, it is less tolerant regarding eye position than the non-pupil-forming approach [300].

The central and also often the most complex and costly element of an *optical see-through* HMD is the combiner [161]. The literature [161, 193] distinguishes three major groups of combiners:

- **Free-space combiners** — The classic design with many subtypes. Most prominent examples are tilted half-tone mirrors as applied by the IHADSS (Figs. 2.2a and 2.7a), curved visor combiners (e.g. JedEye, Meta 2), and birdbath designs [161].
- **Freeform prism combiners** — A solid prism which relays the virtual image based on a total internal reflection surface and lets the real-world image pass through a semi-transparent surface [161].
- **Waveguide combiners** — An optical guide that propagates the light based on several total internal reflection bounces. So-called input and output couplers create a single entrance pupil, where the image from the display is fed into, and often many exit pupils, where the image is reflected to the user's eyes [161]. Figure 2.7b illustrates this approach using the Microsoft HoloLens as an example. It applies three stacked



(a) The pupil-forming design of the IHADSS with tilted, flat combiner (adapted from [259]).

(b) The optics of the HoloLens with three stacked waveguides, in- and out-coupling grating, and 2-D pupil replication [n].

Figure 2.7 – Examples of optical see-through architectures.

waveguides (one per color) and slanted surface-relief gratings as input, redirection, and output couplers [162]. The huge number of other available implementations of that technique are thoroughly reviewed by Kress [161].

Typical Design Challenges & Solutions When designing an HMD to meet the requirements listed in Sec. 2.1.3, two main invariants need to be respected: the Lagrange/optical invariant and the Etendue [161]. These are physical laws of optical systems that describe the correlations between the involved design parameters. For instance, they imply that increasing the numerical aperture of the collimation lens to enlarge the FOV results in unwanted reduction of the eyebox, decreased angular resolution, and larger optics [161]. Another example is the attempt to enlarge the exit pupil and the eye relief [11] in order to improve the viewing comfort. However, this inevitably leads to larger, heavier optics [193].

Luckily, HMD designers have found several ways to evade those invariants. The mechanical adjustment of the exit pupil to fit the user's interpupillary distance is, for instance, available in almost every modern HMD [161]. Also, exit pupil expansion, replication, and other techniques have become very common to enlarge the eyebox of pupil-forming architectures. An example is the 2-D exit pupil replication implemented by Microsoft's HoloLens [162] (see Fig. 2.7b). In-depth explanations and more techniques are found in [161].

Current Research Topics Major research effort is currently put into increasing the FOV (e.g. through optical tiling, partial binocular overlap, advanced lens setups [161, 193]) while simultaneously providing sufficient angular resolution with acceptable rendering effort (e.g. via various foveation approaches [161]). Also, the supply of natural depth cues in a virtual or mixed reality experience is an important goal of many HMD manufacturers. This includes the avoidance of the vergence-accommodation conflict (e.g. through light field displays [280]) and realistic occlusion behavior between real and superimposed virtual objects [161]. Further details as well as the relevance of these current HMD limitations and challenges *in the context of a virtual cockpit* are discussed later in Sec. 3.3.1.

2.1.4.2 Image Sources

The image source is a crucial part of the HMD because many of the requirements listed in Sec. 2.1.3 highly depend on it (e.g. resolution, luminance, contrast, color, size). HMDs profited from the general advancement of display technologies — from early cathode ray tubes using stroke and raster mode [322] to modern flat panel and scanning displays. A detailed review of available image source types is provided by [161, 251]. Basically, this includes all common display technologies from emissive (e.g. OLED) via reflective (e.g. LCoS) and transmissive (e.g. LCD) matrices to scanning displays. One particular difference to the "mainstream" display branch is the special need for very small sizes, wide luminance range, and higher pixel density than in PC monitors or mobile phones/tablets.

[11] Eye relief is usually defined as the distance from the user's eye to the first optical element [193].

2.1.4.3 Head-Tracking and MR Sensors

Accurate and fast head-tracking is required to enable correct alignment of the virtual with the real world. Over the years, many solutions with different advantages and limitations (see [322] for a detailed comparison) have been developed: direct mechanical measurement [e.g. 290], electromagnetic sensing [e.g. 61], optical tracking [e.g. 86], and acoustic/ultrasonic systems [e.g. 305]. To improve accuracy and responsiveness, these are often expanded to "hybrid systems" with an additional inertial measurement unit embedded in the HMD. Furthermore, various motion prediction techniques are usually applied to reduce the impact of system latency [323]. During the last decade one could see a trend from the typical outside-in tracking, where an external sensor tracks the HMD, towards self-contained inside-out tracking [161]. This means that many modern HMDs do not need externally mounted hardware to orientate themselves. Instead, they use integrated cameras to track fiducial markers or object features in the environment [20]. Thales' hybrid optical-inertial inside-out tracking with fiducial stickers for the Scorpion HMD shows that such approaches are also feasible for aircraft cockpits [9].

Fusing information from various other HMD-mounted sensors is very important to create realistic mixed reality experiences. For instance, depth sensing and chroma keying can be applied for advanced composition of reality and virtuality with correct occlusion behavior [20, 314]. Further, several use cases for hand- and eye-tracking sensors exist (e.g. interaction, foveated rendering).

2.1.5 Usage of HMDs in Aviation[12]

Melzer and Moffitt [189] describe HMDs as "efficient and intuitive task enablers" that "can enhance the performance of many tasks by providing information in a new, exciting, and highly personal way." In contrast to conventional monitors, especially the natural presentation — where the user is looking at — is a central benefit as it improves visual scanning and exploring [189]. This section provides an overview of how HMDs have been used in aviation 1) for flight simulators (on ground), 2) for in-flight simulation (in the air), and 3) as actual pilot assistance system in the cockpit.

[12] Parts of this section have been published by the author in [69, 72, 77].

2.1.5.1 Flight Simulators Based on Immersive HMDs

The evolving capabilities of MR- and VR-HMDs make the technology an interesting alternative to conventional flight simulators. In such an XR flight simulator, the pilot wears an HMD and gets immersed into a computer-generated cockpit with virtual out-the-window view. A major advantage of this approach is that it does not require a complex and expensive outside vision projection system. Even better, especially for helicopter simulations, the out-the-window view is not restricted to the projection system anymore — the head-tracked HMD shows the environment wherever the pilot wants to look. This even allows to include the cabin crew into the simulation: For instance, Reiser [258] implemented a simulator to practice crew communication. In many rescue missions, crew members look out the cabin door to monitor the side and back of the helicopter and assist the pilot through voice commands. As conventional dome projections do not cover these areas, an HMD was used to show these parts of the surroundings.

The second big advantage of XR simulators is that they do not need a full cockpit mock-up. Only elements required for interaction must be physically there — for instance cyclic stick, collective lever, and pedals. The rest of the environment — cockpit shell, visual displays, et cetera — can be digitally generated via the HMD. This saves costs and effort for buildup and maintenance, reduces space requirements, and makes it easy to simulate different cockpit architectures without building physical simulator mock-ups. A new flight deck layout can just be loaded as a 3-D model in the display software.

Typical challenges are limitations of the HMD hard- and software (FOV, resolution, wearing comfort, frame rate, etc.), cumbersome input methods (e.g. caused by lack of haptic feedback), and simulator sickness [10, 224].

Training The idea of an XR flight simulator is not new. More than 20 years ago, the Technical University of Darmstadt already researched on how to realize pilot training with VR-HMDs [50, 263]. In cooperation with EADS and Lufthansa, these first prototypes were further developed into a VR procedure trainer [17]. Their goal was to reduce the training time required on costly full flight simulators. However, due to the complicated user input methods and the limited HMD capabilities at that time, these early implementations never really caught on. With advancing XR technologies, the work on HMD-based flight training continued [e.g. 135, 208, 333, 354] until an important milestone was reached recently: In 2021, VRM Switzerland (now: Loft Dynamics) presented the first VR flight simulator that obtained EASA qualification as flight training device [329]. This means that hours accumulated in their VR helicopter simulator count as actual flight training time.

(a) Simulator setup on a motion platform with a pilot wearing a VR-HMD — The minimal cockpit mock-up is required to receive user input and to provide haptic feedback.

(b) Mixed reality interaction concept — The users see a virtual representation of their body and interact with real input devices which have a virtual twin in the VR view.

Figure 2.8 – Loft Dynamics's virtual reality flight simulator for the Robinson R22 — an EASA-qualified training solution [328].

Figure 2.8a shows their setup featuring a motion platform and a minimal cockpit mock-up. As illustrated in Fig. 2.8b, the latter is required to provide a realistic experience for the pilots when pushing buttons or interacting with switches. Furthermore, Loft Dynamics developed a full body pose tracking system which shows a virtual representation of the pilot's body — without requiring them to wear the typical hand-tracking gloves [328].

An alternative approach to obtaining a realistic user interaction is taken by Kratos [158]. Instead of showing virtual twins of the cockpit and the pilot's body, they use a video-see-through HMD and chroma keying to combine a stereo view of real elements (flight deck mockup, pilot body, etc.) with a virtual out-the-window view. A key part of many current XR simulators is the high-resolution video-see-through HMD Varjo XR-3. Its enhanced capabilities brought VR/MR flight simulation to a new level and made it an interesting choice for a wide variety of organizations. Varjo names the Finnish Air Force, the U. S. Navy, Dassault Aviation, and the training company FlightSafety International as users of their devices [320].

While Loft Dynamics and Kratos prove that meaningful flight training is possible with VR-/MR-HMDs, it still requires significant effort, expertise, and custom-made mixed-reality solutions. A pure virtual setup with consumer-grade hard- and software only is not (yet) able to reach the capabilties of full flight simulators — not even for basic training like cockpit familiarization [10].

Cockpit Design Prototyping XR simulators have also been successfully used in an early stage of the flight deck design process [e.g. 32, 133, 137, 227]. The helicopter manufacturer Bell could drastically reduce the cost and time required to design their futuristic concept aircraft FCX-001 by using HTC VIVE VR goggles [133]. They argue that having a virtual full-scale prototype from the beginning allows them to get better early feedback because the pilots can sit in the virtual version of the cockpit very soon. Thereby they can assess visibility, accessibility, and ergonomics much better than in the small-scale prototypes that are commonly used in the early design stages. Similar advantages are reported by Oberhauser et el. [224], who implemented a mixed-reality setup with a partly physical cockpit mockup and additional virtual user inputs based on finger-tracking [8]. Their extensive research revealed a degradation of flight performance compared to a conventional simulator [225]. Moreover, the time required to interact with the cockpit was higher in the virtual flight simulator. Nevertheless, they conclude that an XR simulator can be a viable tool in early phases of the design process — but it cannot entirely replace full hardware mockups.

Flight Guidance Symbology Research Besides the mentioned applications for crew training and in the cockpit design process, XR flight simulators are also used to conduct research on novel pilot assistance systems. For instance, Schmerwitz et al. [266, 267] used a simple VR-HMD setup to evaluate conformal landing symbologies for DVE in a part-task simulation. Similarly, Dreyer et al. [52] evaluated a HUD symbology through VR simulation.

From a technical perspective, the presented XR flight simulators have several commonalities with the virtual cockpit developed in this dissertation. However, the main difference is that their purpose is to replicate conventional cockpits in a simulation environment, whereas the proposed virtual cockpit is not a simulation tool but part of an actual aircraft.

2.1.5.2 In-Flight Simulation with HMDs

HMDs can also be used in actual flight training to simulate certain scenarios by adding virtual elements to the pilot's real view. Bachelder et al. [13] developed an MR in-flight simulator by integrating a video-see-through HMD into a Learjet cockpit. The evaluation pilot[13] sees a video stream of the real flight deck where the cockpit window areas are replaced by a computer-generated out-the-window view. The great advantage of this "simulator" is that it provides the benefits of actual flight tests (e.g. real flight dynamics) but reduces typical risks and problems. As an example, their work demonstrates the training of aerial refueling, which usually involves the risk of operating close to the tanker aircraft and the problem that abnormal and emergency situations can hardly be trained safely. With their setup, such scenarios can be simulated without risk because the tanker as well as the rest of the environment is computer-generated. Other use cases for a MR in-flight simulator could be formation flying or helicopter DVE training. One could, for instance, train brown-out landings without the trouble of an actual brown-out. Somewhat similar solutions have been developed with optical see-through HMDs. For example, Red 6 [254] describes a system which projects adversary aircraft into a fighter pilot's natural out-the-window view to conduct air combat training with reduced risks, less costs, and more efficiency. Recently, in 2020, the works of Bachelder have been revived by Klyde et al. [144] who created their "Fused-Reality Flight" system with commercial-of-the-shelf hardware.

2.1.5.3 HMDs in the Actual Cockpit — Today and in the Future

Optical see-through HMDs have been used as pilot assistance devices on the flight deck for many years — however, only in specific, mostly military scenarios. The central idea is to present aircraft state and flight guidance information as well as missing outside visual cues superimposed onto the pilot's natural out-the-window view.[14] This "unlocks the pilot from the interior of the cockpit" [190], thereby reducing head-down & information scanning time and avoiding re-accommodation of the eyes because important information is shown as collimated overlay [191].

[13] The second pilot is a safety pilot having the normal out-the-window view.

[14] The key advantage over aircraft-fixed HUDs is that HMDs can superimpose information over the pilots' entire field of regard, no matter where they look at [191].

Current Use Cases & Symbology Design Paradigms A first use case was off-boresight targeting via the HMD, which enhanced the combat capabilities [191]. Over the years, this was expanded with head-up depiction of important aircraft state information, augmentation of the natural sight with sensor imagery, and rather complex flight guidance symbology. Probably the most important HMI design paradigm in this context is the concept of "conformal symbology". The idea behind that is to show "synthetically generated symbols in spatial relation to real world objects" [238] or in other words "overlying its far domain counterpart" [350]. Well-known examples are tunnel-in-the-sky, horizon line, or obstacle highlighting [238]. Symbology with no physically viewable counterpart (e.g. tunnel-in-the-sky) is sometimes also referred to as "*virtually* conformal" [87]. Closely related is the concept of "scene-linking". Scene-linked symbols are commonly used to spatially integrate information from the display domain into the far domain so as to mitigate divided-attention issues [100, 183, 269, 276]. For instance, placing a virtual traffic sign as speed or altitude indicator at a world-fixed location next to the desired flight path is considered scene-linking. A detailed presentation of state-of-the-art HMD symbology is given in Sec. 2.3.

Benefits & Limitations Overall, HMDs are often associated with efficient decision making, reduced workload, and increased situation awareness [190]. A common definition of the latter is given by Endsley's three-stage model, which defines situation awareness as "the perception of the elements in the environment within a volume of time and space (level 1), the comprehension of their meaning (level 2), and the projection of their status in the near future (level 3)" [64]. Head-up symbology was found to improve flight path tracking [88, 145, 173] and detection of *expected* events [87]. However, head-up symbology — especially when presented in non-conformal manner — may lead to clutter, attentional tunneling,[15] impeded detection of *unexpected* and non-salient events, and inattentional blindness [87, 88, 98, 145, 173]. Extensive reviews of costs and benefits are provided by Fadden et al. [88] (HUDs) and Knabl [145] (HMDs).

[15] Attentional tunneling is "the allocation of attention to a particular channel of information, diagnostic hypothesis, or task goal, for a duration that is longer than optimal, given the expected cost of neglecting events on other channels, failing to consider other hypotheses, or failing to perform other tasks" [346].

Concepts for Future Cockpits[16] As early as 1986, Furness [107] envisioned how a future “Super Cockpit” should look like. Among other technologies, his visionary system employs an HMD to immerse the pilot in a virtual environment. He explains that the intent of this “radical departure from conventional crew station design [...] is to provide interfaces which are intuitive and easy to use and that take advantage of our natural perceptual mechanisms in the design of a virtual 3-D world of sights and sounds” [107]. Due to the lack of the required technology at that time, Furness could only describe his ideas in words and figures but not actually realize them.

Meanwhile, HMDs have been gradually introduced to flight decks and several of Furness’ visions have been implemented (e.g. conformal overlays in AR-HMDs, spatial audio, etc.). However, this happened only at a slow pace and for very specific applications. This may change when the capabilities and the cost-benefit ratio of HMDs further improves. Concepts originally developed for the military might soon reach more and more civil helicopters if they lead to a quantifiable benefit for the operating companies [cf. 331]. For civil airliners, the NASA assumes that a viable business case may be “HUD equivalence” [7]. This means that — if the technology is ready — HMDs may be used with the same operational credits as HUDs (i.e. reduced minima; see Sec. 2.2.3). The application of an HMD can make sense when HUD installation or retrofit is not cost-efficient or simply not possible due to space or weight restrictions. Also, a return-on-investment advantage or better properties (e.g. larger FOV and boresight-independence) can be reasons to choose an HMD [7].

Besides this rather short- to medium-term outlook, several more long-term visions for HMD-based future cockpits have been developed. All these have in common that they enforce the already existing trend towards relocating more and more information from the instrument panel onto the HMD. Several patents [e.g. 118, 140, 356] describe cockpits where HMDs and other display means create large 3-D control stations and wide virtual or augmented out-the-window views as imagined by Furness. Further, Comerford and Johnson [37] theoretically elaborate the potentials of a conventional cockpit augmented with virtual user interfaces. Finally, as seen in Fig. 2.9a, the rotorcraft manufacturer Bell dreams of a highly computer-assisted cockpit without physical controls and screens in their futuristic concept helicopter FCX-001 [136].

[16] Note that major parts of this section were written after the studies of this dissertation were completed because many works mentioned here were not published when the author started his work.

Being already in service, the Lockheed Martin F-35 Lightning II fighter aircraft showcases what is possible and what might be available in a broader range of cockpits in the future. It applies an HMD instead of the HUD that was obligatory in previous-generation fighter jets. Thanks to six infrared cameras mounted all around the aircraft, the HMD enables the pilot to "look through" the aircraft structure [279]. A somewhat similar system is tested on the Bell V-280 Valor tiltrotor aircraft [36]. According to Arthur et al. [7], such HMD-based vision systems might enable VMC-like procedures in all-weather conditions ("equivalent visual operations") and "better-than-visual" operational capability (see Sec. 2.2 for more details on vision systems as a whole).

(a) Mockup of Bell's FCX-001 cockpit using an optical see-through HMD as the only display [o].

(b) Illustration of the "wearable cockpit" envisioned for the sixth-generation fighter jet Tempest [14].

Figure 2.9 – Concepts for future cockpits.

A very important trend is that HMDs seem to play a key role in the cockpit of the sixth-generation fighter aircraft which are currently developed. The Tempest fighter aircraft engineered by a consortium led by BAE Systems will have a "wearable cockpit" based on BAE's Striker II HMD [14]. Naturally, only little information on the status of such programs is publicly available. Figure 2.9b shows a news release illustration where an HMD creates a virtual cockpit with see-through-the-fuselage view and virtual instruments replacing the conventional instrument panel. The Tempest consortium states that they are "working towards [their] concept of cockpits without a single physical dial or screen" [260]. Simultaneously, the European Future Combat Air System (FCAS) program considers the implementation of a virtual outside vision with complex operational information presented on an HMD [66].

2.2 Vision Systems — Re-Creating the External View on a Display[17]

The out-the-window view is an important information source for every pilot. Under visual flight rules (VFR), the pilot uses outside visual cues to control the aircraft attitude, to navigate, and to see and avoid terrain, obstacles, and traffic. Even airliner crews operating under instrument flight rules (IFR) are required to see certain runway features in order to continue the landing and descend below the decision height.[18] Vision systems are used when the pilot's natural vision of the environment is degraded. They display synthetic or sensor-based imagery often combined with symbology in order to complement, enhance, or even replace the pilot's limited out-the-window view. As sketched in Fig. 1.2, both parts of a vision system — sensors/databases and displays — are an integral part of state-of-the-art DVE solutions.

This section summarizes the status quo of vision systems and gives an outlook on the near and far future. It begins with an analysis of the natural out-the-window view, which has to be replaced by the vision system. This is followed by an overview of common vision system types & classifications and an explanation of what is currently allowed when using such systems. Thereafter, research on novel helicopter DVE mitigation systems and an excursus on the role of automation is presented. Finally, the state-of-the-art external scene representations for helicopter operations are reviewed.

2.2.1 Natural Out-the-Window View as Baseline

The requirements definition for a visually-equal vision system is often started by analyzing the properties of the natural out-the-window view, which is of course heavily influenced by the capabilities of the human vision. The problem is that the eyes — which are only one part of this very complex sense — can hardly be described with the properties known from camera specifications. For instance, one cannot state an overall resolution of the eye since the 120 million rods and 6 million cones are not as evenly distributed over the retina as the cells on a digital image sensor [105]. The central fovea

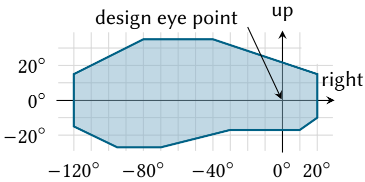
[17] Parts of this section have been published by the author in [69, 77].
[18] The only exception to this are special CAT III operations with autoland systems [91].

is densely packed with color-sensing cones whereas the peripheral areas of the retina are populated by rods. The latter are very sensitive to motion but not able to perceive color. By the same token, the FOV of the human visual system can cover up to 150° vertically and 218° horizontally [288]. However, the brain is not able to process all information equally. Tasks like reading are always performed with the central part of our vision where the cone density is the highest [85].

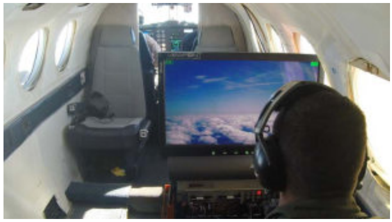
Having these characteristics in mind, one can still relate the human visual acuity to a pixel-based resolution. Humans with normal visual acuity — often referred to as 20/20 vision — are able to resolve one arc minute (1/60 deg) [105]. The related distance on the fovea (~5 μm) equals double the distance between two rows of cones (~2.4–2.6 μm), implying that one unstimulated cone resides between two stimulated cones [85]. The one-arc-minute stroke width of the famous Snellen letters on visual acuity charts implies that one pixel per arc minute or 60 pixels per degree (ppd) are required for a display to conform to normal visual acuity. Even though one arc minute is probably the most used resolution requirement, this value should not be considered as an upper limit since many humans have better than 20/20 vision and hyperacuity allows us to discriminate details of a few arc seconds in certain constellations [338]. Lloyd et al. [171] name a few other methods of how to define "eye-limited resolution" from which the determination via an asymptotic performance threshold seems the most practicable.

Resolution and FOV are important factors for describing the capabilities of the human visual system. Nevertheless, many other parameters, especially color gamut and depth, dynamic range, and sensitivity, must also be considered. Furthermore, the interaction of both eyes, which allows for stereoscopic vision, plays an important role, at least in the near domain. On the other hand, it must be mentioned that the eyes can only sense the environment within the visible spectrum (~400–750 nm [85]). Certain vision systems overcome this limitation by using sensors working in the infrared and other parts of the electromagnetic spectrum. Further details on the challenges of replicating the reality on a display are provided later in Sec. 3.3.1.

Besides these eye-related aspects, the pilots' view of the external scene is additionally restricted by the cockpit windows. Figure 2.10a sketches the minimum FOV for the pilot compartment view of transport airplanes as recommended by the advisory circular 25.773-1 [89]. In general aviation and



(a) Left-seated pilot's field of view as recommended for transport category airplanes by AC 25.773-1 [89].



(b) Pilot using NASA's XVS monitor installed in the cabin during test flights [156].

Figure 2.10 – Cockpit external vision.

rotary-wing aircraft, the provided window area highly depends on the aircraft type. Smith and Foster [282] present the available FOV in various helicopters.

2.2.2 General Classes of Vision Systems

Vision systems can be grouped into systems that try to equally replace the out-the-window view and systems that try to improve the (degraded) external vision. These are introduced in the following together with the classification scheme commonly used by the aviation community.

2.2.2.1 Equivalent Vision — External Vision Systems[19]

So-called external vision systems (XVS) try to equally replace the pilot's natural out-the-window view by forward-facing, visible-spectrum cameras delivering a video stream that is displayed on cockpit monitors. According to the NASA, the stated "equal replacement" implies that the pilots can conduct common out-the-window tasks like traffic detection with the same level of safety and performance as with their natural vision through conventional cockpit windows [157]. Conversely, this means that such a system does not help against classic DVE since adverse environmental conditions are just replicated. However, it is suitable for cases like NASA's low-boom supersonic

[19] Parts of this section have been published by the author in [69].

aircraft, which has an aerodynamically optimized, lancet-shaped nose without forward-facing cockpit windows [157].

It is important to note that — in contrast to *sense and avoid* systems — NASA's XVS does not perform automatic target detection via image processing but leaves this task to the pilot. Minwalla et al. [203] showed that camera systems with such automatic-detection algorithms can "exceed typical visual acquisition ranges under typical visual meteorological conditions."

NASA started their work with a theoretical assessment of human vision and came to the same conclusion as above that 60 ppd is "a minimum but perhaps not sufficient resolution requirement [. . .] for human vision equivalence" [15]. For their further work, they decided to follow a more hands-on approach to check human vision equivalence: They selected relevant tasks and compared the pilots' performance with the XVS against their results with natural vision. To do so, they defined safety and performance equivalence via the three tenets of VFR operations: *see-to-follow*, *see-and-avoid*, and *self-navigation*.

Their pre-calculations reveal that "see-and-avoid and see-to-follow performance requirements are nearly double" [15]; while prior research already showed that the vision requirements for successful self-navigation are lower than for both other maneuvers. For example, pilots are able to conduct approaches and landings with severely restricted FOV [240] and resolution [108]. NASA's first flight campaign proved the theoretical calculations. The tested XVS, which had a FOV of $51° \times 30°$ with 63 ppd pixel density, did not achieve an equivalent visual capability [277]. Besides display resolution, camera dynamic range and contrast appeared to be important factors influencing the detection of other aircraft.

A later iteration of NASA's XVS, however, showed that equivalent or even better performance in a traffic detection task is possible [156]. To reach this, a distinctly better camera and monitor system was installed: 3920 px × 2400 px resolution and $36° \times 24°$ FOV resulted in a pixel density of 109 ppd horizontally and 100 ppd vertically. Further, the usage of contrast-enhancing image processing significantly improved the detection of small aircraft. Figure 2.10b shows the test setup: A test pilot monitors traffic on the XVS display mounted in the cabin, while the second test pilot performed the same task through the cockpit windows.

2.2.2.2 Improved Vision — Synthetic, Enhanced & Combined Vision Systems

The U. S. and the European regulatory authorities (FAA, EASA) and the respective standardization organizations (RTCA, EUROCAE) distinguish between

- synthetic vision systems (SVS),
- enhanced vision systems (EVS), and
- combined vision systems (CVS) [80, 90].

This classification is based on the type of data used to generate the displayed image. Generally, environmental data can either be stored in databases or be gathered by aircraft-mounted sensors. All systems have in common that they want to provide a better vision than the degraded out-the-window view.

A system is called SVS if the image is created from information of a coordinate-referenced database [80]. By contrast, an EVS is "an electronic means to provide a display of the forward external scene topography through the use of imaging sensors, such as forward-looking infrared (FLIR), millimeter-wave (MMW) radiometry, MMW radar, and/or low-light-level image intensifying" [90]. An SVS requires correct aircraft position and attitude measurements to generate a correctly positioned and aligned synthetic view. An EVS does not have this requirement since the correct alignment of the image is implicitly given by the aircraft-mounted imaging sensor. Another problem of SVS is that databases always contain the state of the environment when they were created. This means that the information can be outdated or in general incomplete. A sensor, on the other hand, measures the current state implying that it can also detect recent changes. However, the sensor range is limited and the detection probability and information quality depend on the current properties of the surrounding atmosphere [261]. For instance, a lidar is 3-D capable and provides high-resolution data. However, it can hardly penetrate dense DVE [187]. The longer electromagnetic waves of MMW radars, on the other hand, can better see through small atmospheric particles but come with the trade-off of a low resolution. A database does not have these restrictions.

A CVS combines the features of SVS and EVS. As sketched in Fig. 2.11, it processes data from both databases and sensors to create the computer-generated image of the environment. Of course, the integration of both data source types adds system complexity. Nevertheless, this is often worth the effort

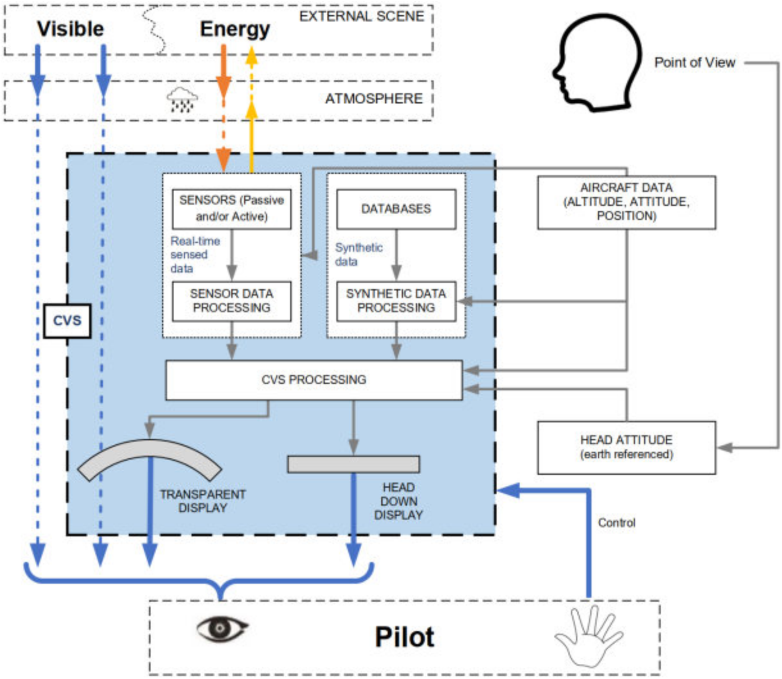


Figure 2.11 – Modules of a combined vision system [81].

since a CVS mitigates the described problems of the uncombined systems. DLR's research project ADVISE-PRO [150] thoroughly carved out the advantages of this approach: With their developed system, Korn et al. [148] showed how MMW radar and other data sources can be fused to ensure the accuracy and integrity of the navigation information for board-autonomous final approach and landing in low visibility. Furthermore, several HMI concepts were implemented and evaluated [151].

As a side-note, Fig. 2.11 also underlines that the introduced terms can include either display type: conventional PMDs as well as transparent displays (HUDs, HMDs). While reading literature, one should be aware that not everybody adheres to this terminology. For instance, the term synthetic vision is occasionally also used for non-database systems. In contrast to XVS, which are in research status, SVS and partly also EVS and CVS are state-of-the-art on modern flight decks.

2.2.3 Current Vision System Regulations

Operational Credit It is important to note that — according to current FAA and EASA regulations — the above-mentioned systems do not create operational benefits. In other words, pilots are not allowed to operate below the generally required flight visibility minimums: If the natural out-the-window view does not meet the prescribed minimums, the flight cannot be conducted even if the vision system enables the crew to see far enough. Nevertheless, such systems have been shown to increase flight safety as they enhance the pilots' situation awareness and may also help when inadvertently entering instrument meteorological conditions (IMC) [355].

Only with a so-called "enhanced flight vision system" (EFVS)[20] and only for straight-in approaches, the authorities grant operational benefits. An EFVS combines EVS sensor imagery with flight guidance symbology via a HUD or "an equivalent display" [95], which explicitly does not include head-down PMDs. Until recently, all available EFVS comprised a HUD. In 2020, however, the EASA certified the first EFVS with an HMD: the ClearVision™ EFVS with the SkyLens™ HMD by Universal Avionics [62].

The general idea of an EFVS is that the pilots conduct the approach following the normal procedures. However, for the visual segment – which starts at the decision altitude/height (DA/DH) or minimum descent altitude (MDA) – they use the sensor image instead of the degraded natural out-the-window view. This means that an approved EFVS permits the pilots to descend below DA/DH or MDA if the required visual references of the runway can be identified through the EFVS [95]. Regarding the further procedure, the FAA defines two types of EFVS operations: The first demands natural vision from 100 ft above touchdown zone elevation (TDZE), while the second allows the whole visual segment including touchdown and rollout to be performed with EFVS vision only [92]. Details are sketched in Fig. 2.12. The feasibility and safety of such operations was confirmed by several research studies [e.g. 149, 153–155].

Helicopters The regulations described above were mainly introduced with fixed-wing operations in mind. Nevertheless, especially for helicopter-typical missions, modern vision systems are needed. These can increase the safety of current VFR operations and in the future also expand the operational

[20] EASA uses the term "EVS" as a synonym for FAA's "EFVS" [80].

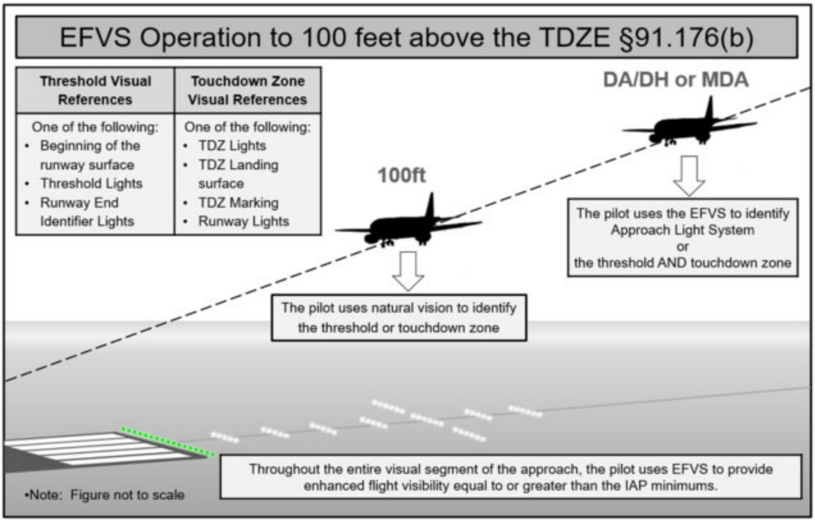


Figure 2.12 – Enhanced flight vision system operations to 100 ft above touchdown zone elevation. Note that the second type of EFVS operations enables proceeding to touchdown and rollout with EFVS vision [93].

envelope. In recent years, the industry and the regulatory side launched several initiatives addressing rotorcraft-specific topics [312, 331]. For example, the EUROCAE published its first minimum aviation system performance standards (MASPS) specifically for helicopter CVS [81]. Furthermore, modern helicopter avionics systems with SVS like Helionix by Airbus [41] or HeliSure by Collins Aerospace [128] became commercially available in recent years.

2.2.4 Novel Helicopter DVE Mitigation Systems

Section 2.2.2.2 specified what is currently installed on modern aircraft. The research community is naturally several steps ahead of these. Especially in the active research on helicopter DVE mitigation solutions, novel vision systems play an important role — even though they are only one part of the solution. As described in the introduction, current research follows two goals: 1) simplify the flying task through advanced flight control & management systems, and 2) replace the missing outside visual cues through auditory, tactile, and visual display & cueing systems (see Fig. 1.2). Aircraft-mounted sensors and databases form the basis of these DVE mitigation solutions. This section presents the various types of helicopter DVE systems — classified according to their properties and capabilities.

NIAG's Classification No single sensor or database meets all the requirements under all possible DVE conditions [220]. Thus, systems that fuse information from databases and multiple types of sensors became state-of-the-art in today's research. These advances also raised a need for new system classifications beyond the terms used by current regulations. The NATO Industrial Advisory Group (NIAG) recommends a helicopter DVE system classification with four classes [220]. Figure 2.13 shows that class 4 represents the most basic system, while the other classes incrementally add further capabilities. A class 1 system features the most advanced technologies.

A prerequisite for all classes is GPS navigation, a radar altimeter, and other non-DVE-specific standard equipment. Class 4 systems are similar to the already introduced SVS. They rely on digital terrain elevation data and other databases, include no sensor, and require the pilot to interpret the data. Class 3 systems are comparable to what is called CVS above. They add an enhanced vision imaging sensor to complement the synthetic view with real-time imagery. Similar to class 4 systems, the pilot must interpret the data to detect potential hazards. Class 2 systems add forward-looking, active 3-D sensors like lidar and fuse data from all available sources. An important feature is that class 2 systems include data interpretation functions. They detect obstacles and provide warning and guidance cueing. Finally, class 1 systems complete these features with automatic flight guidance. They can use the available data to enable (semi-)automatic operations via an advanced flight control system.

The superiority of class 2 systems compared to database-only class 4 solutions is shown by Münsterer et al. [214]. They elaborate how the typical registration errors of terrain databases and the inaccuracy of aircraft position measurements can lead to intolerable misplacement of conformal symbology. Their sophisticated compensation techniques can reduce these issues but can only be safely used in limited operational environments without man-made obstacles and vegetation. Their flight tests of a class 2 system, on the other hand, prove that the additional complexity and cost of such solutions pay off through high conformity between symbology and real world.

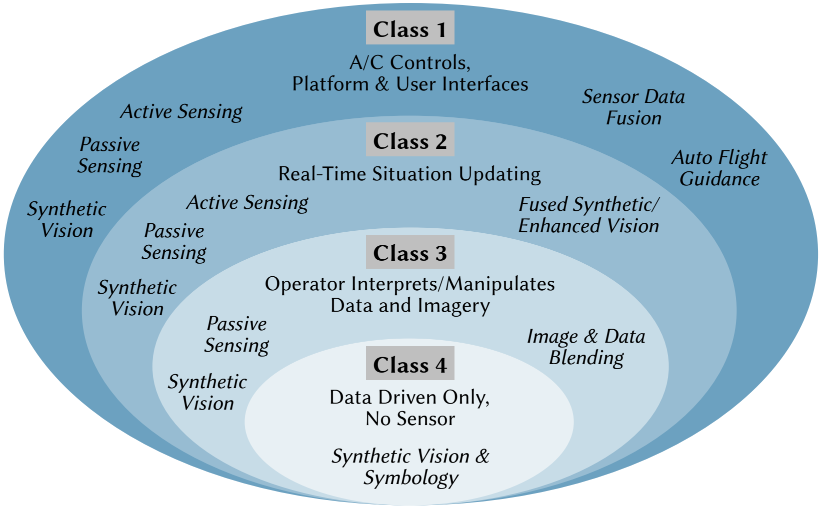


Figure 2.13 – NIAG's helicopter DVE system classification (adapted from [220]).

Cross' Classification Cross [42] provides another classification scheme, which includes suggestions for future visibility minima regulations. He argues that the multitude of possible system architectures together with several potential concepts of operation from military rotorcraft to civil fixed-wing aircraft leads to new and complicated tasks for the regulatory authorities. He further reasons that modern vision systems do not fit into the classic VFR/IFR regulatory scheme. As a first step, he therefore proposes a classification of DVE systems which is based on the actual capabilities of the system instead of its system architecture/components (cf. SVS, EVS). This idea is borrowed from the categorization of instrument landing systems into CAT I/II/III, where the specific system architecture (antennas, redundancy, etc.) is not relevant for the pilot as each category has clearly defined capabilities.

Figure 2.14 shows Cross' space of possible DVE systems. It is spanned by two axes that define to which degree both sensor imagery and sensor data are used. In this context, "sensor data" implies that the sensor output is interpreted to obtain three-dimensional information about the environment. This is often accomplished with 3-D-capable sensors like lidar but also processing of 2-D images is possible [47]. In contrast, "sensor imagery" comprises non-interpreted visual images from the above-defined EVS sensors.

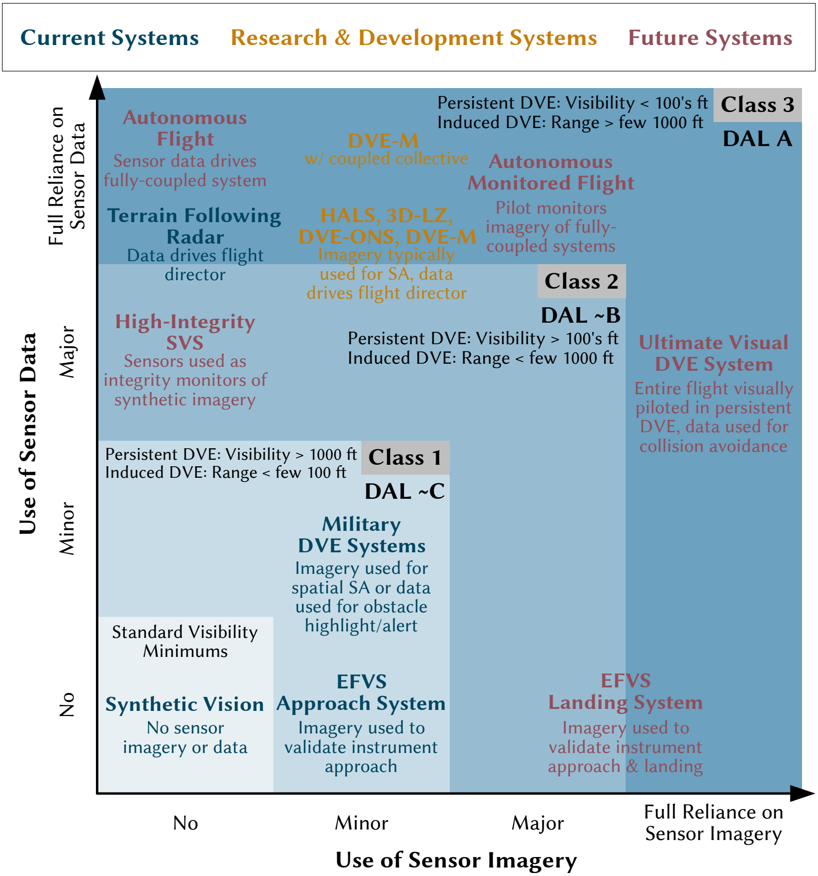


Figure 2.14 – Cross' DVE system capability classes (Sierra Nevada Corp. [42]).

Based on those axes, he defines areas representing different capability classes. If no sensor is used (i.e. SVS), the pilot must comply with the standard visibility minima (lower left area). With increased use of sensor data/imagery, the visibility minima for persistent and induced DVE could be reduced step-by-step. These new categories are represented by class 1, 2, and 3, where the latter contains the most capable DVE solutions used in the lowest visibility. Of course, this implies that the further right or top a system is positioned, the more reliable this system must be. Cross notes that the class boundaries are roughly aligned with the standardized development assurance levels (DAL) and the respective failure condition classes (minor, major, hazardous, catastrophic). Transferred to operations, Cross explains that class 1 systems (DAL C) can only serve as situation awareness aid providing non-flight-critical information. Class 2 (DAL B) covers systems that "can be used for decision making [...], but typically require mitigations outside the DVE system to compensate for their safety level" [42]. Owing to their high integrity and redundancy (DAL A), class 3 systems can be used without natural out-the-window view [42].

Figure 2.14 shows how actual DVE systems can be assigned to the proposed classes. The status quo of the systems is color-coded: fielded solutions in blue, research and development programs in orange, and potential future systems in red. The lower area of the graph contains the familiar SVS and the EFVS introduced in Sec. 2.2.3. In the upper area, the major research programs of the U. S. Army like 3D-LZ ("3-D Landing Zone") and DVE-M ("DVE-Mitigation") are mentioned. These are presented in detail in Sec. 2.2.6 and 2.3.

It should be noted that Cross' classification is a high-level conceptual approach which needs to be backed and detailed by further research. Nevertheless, Cross' as well as NIAG's classification schemes seem to be good starting points on the path to operational benefits for DVE mitigation systems.

2.2.5 Excursus: The Role of Automation

The presented classification schemes show again what the author already emphasized in the introduction: Vision systems are only one part of state-of-the-art DVE solutions. The other pillar are advanced flight control and management systems (cf. Fig. 1.2). All components of the DVE solution may involve the automation of tasks that were previously performed manually.

Information Processing & Automation Parasuraman et al. [232] describe a model for human-machine interaction with automation which can be perfectly applied to this context (see [113]). From a four-stage model of information processing, they derived four functions of a human-machine system:

1. information acquisition,
2. information analysis,

3. decision selection,
4. action implementation.

For each of these, a certain level of automation can be implemented. Applied to DVE systems, a CVS presenting a fused picture of several sensors and databases has a considerable level of information acquisition automation. The data interpretation, the decision-making, and the final action, however, are still done by the pilot. In contrast, highly automated monitored flight as described by Cross in Fig. 2.14 delegates the majority of tasks in all four classes to the automation.

Levels of Automation & Autonomy Anderson et al. [5] provide a taxonomy that defines different levels of automation: Their lowest four levels describe systems where the "pilot is the primary monitor of the flight environment". These range from *no automation* (level 0) via *task assistance* (1) and *partial automation* (2) to *highly automated* (3). Above these first four levels, the "automation is the primary monitor of the flight environment": In *fully automated* flight (level 4), the machine can handle most situations automatically, but the pilot still monitors the execution and has the full authority. Level 5 describes an *autonomous* system where the automation can fully replace the pilot in every possible situation.

This general notion of automation can be perfectly applied to modern helicopter flight control systems (FCS). The lowest level of assistance is provided by the common low-authority stability augmentation systems. Upper control modes like *rate command*, *attitude command*, or even *translational rate command* further automate the piloting task [117]. Such simplified aircraft control can improve the handling qualities, free attentional capacities, reduce workload, and increase safety [220]. The NIAG recommends at least an *attitude command* system for DVE [220]. Higher automation levels can use sensor data to guide the helicopter along an obstacle-free trajectory [357]. The latest CH-53K helicopter shows that such higher-level control automation becomes more and more available in modern rotorcraft. The CH-53K is, for instance, able to automatically decelerate and approach a hover position, which is then held by the FCS [283]. The pilots initiate the maneuver by a button-press, monitor the execution, and – if desired – modify the flight path via simple control inputs. Further specific examples of research on highly automated FCS are described later in Sec. 2.3. Aside from fielded helicopters, the U. S. Army has even demonstrated *autonomous* approach and landing capabilities in several experiments conducted with various specially equipped research helicopters [298].

In summary, the level of automation will increase as 4-axis autopilots, automatic position hold, hands-off trajectory following, and sensor-based obstacle avoidance become the norm on modern helicopters. Nevertheless, the review of current research allows the prediction that human pilots will still be in command in the foreseeable future: They will monitor the automation, make important decisions, and take over control in certain situations, in which full automation is not possible (yet). This implies that — even though the pilots' tasks will change — they will still require situation awareness and therefore need display and cueing systems. Current research has to focus on how the displays must be adapted to the new requirements of piloting with higher automation levels.

The dissertation does not further detail modern FCS because flight control automation is not its focus. Still, the work uses DLR's own research FCS with various upper modes for the experimental evaluation of the developed virtual cockpit. Thus, the chapter that introduces the simulation environment contains more details on state-of-the-art upper modes (see Sec. 4.2.2). Moreover, the final conclusion in Sec. 8.2 discusses what increasing automation means for a virtual cockpit.

2.2.6 External Scene Representations for Helicopter Operations in DVE

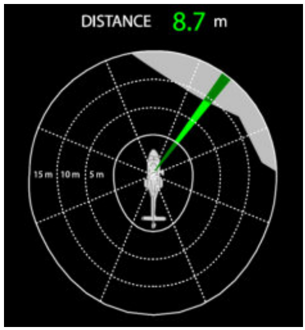
The sections above gave a general overview of different vision system classes. This section presents a review of specific systems and research programs that generate an advanced external view for helicopter operations in DVE. While the relevant sensors and databases are mentioned, the focus will be on the various visualizations. Emphasis is also placed on the differences between visualizations for opaque PMDs and transparent HMDs. Both are important for this dissertation because an opaque VR-HMD will merge characteristics of both worlds. The description is divided into two parts: 1) the representation of obstacles in the near surroundings of the helicopter, and 2) the visualization of terrain and long-range obstacles or objects in general. Even objects that are no imminent hazard may be important for the pilot as landmarks for navigation or as visual cues for motion perception.

2.2.6.1 360-Deg Near-Field Obstacle Warning Systems[21]

The tail and the main rotor are the most vulnerable parts of a helicopter and are predominantly involved in object collisions [125]. The fact that they are only hardly visible from the pilot's seat poses a hazard, especially when helicopters are maneuvered sideways and backwards during low-speed, near-ground maneuvers in confined and unprepared areas. For these reasons, an adequate obstacle awareness and warning system (OAWS) must provide a 360-deg view of the near field around the ownship.

State-of-the-art solutions employ multiple sensors to obtain 360-deg coverage around the ownship. Sensors are preferred over databases because high precision of environmental data is required when the helicopter is so close to obstacles. Further, the fact that many unknown hazards can appear in such situations makes sensors indispensable. A rather short detection range is usually enough as the relevant maneuvers are performed with low speed.

(a) Illustration of the functional principle and the sensor field of view of the Rotorstrike Alerting System by Airbus Helicopters [332].



(b) The display of the Obstacle Proximity Lidar System by Leonardo (pres. slides of [27]).

Figure 2.15 – Examples of 360-deg near-field obstacle warning systems.

As illustrated in Fig. 2.15a, the Rotorstrike Alerting System (RSAS) by Airbus Helicopters applies four commercial-of-the-shelf radar sensors. The flight-tested prototype offers $360° \times 10°$ FOV, 80 m range, less than 10° azimuth resolution, and 0.1 m range resolution [332]. The zone radar by Cassidian (now

[21] Parts of this section have been published by the author in [72], © 2021 IEEE.

Hensoldt) uses four to five radar sensors with 115° × 30° FOV per unit [211]. Their TRL 6 prototype has 3° azimuth and 5° elevation resolution and detects running persons in “more than 100 m” [211]. Similarly, the U. S. Army applied four “bumper” radar sensors covering 360° × 36° on a UH-60 Black Hawk helicopter. In contrast to the others, the concept envisages gimbal-like mountings to keep the sensor plane parallel to the earth or intentionally tilt it during climb and descent [201]. Further, a distributed aperture system with six staring infrared sensors was installed on the Bell V-280 Valor tiltrotor aircraft to provide an unobstructed 360-deg view for all crew members [36]. Finally, Leonardo offers an EASA-certified Obstacle Proximity Lidar System (OPLS), e.g. for their AW 139 helicopter. The system uses three lidar sensors to detect obstacles “as thin as a few cm” with 0.1 m accuracy and 25 m range [27].

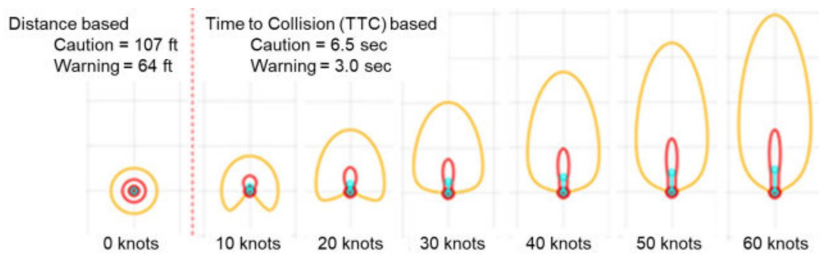


Figure 2.16 – Speed-dependent threat level representation developed by the U. S. Army [291].

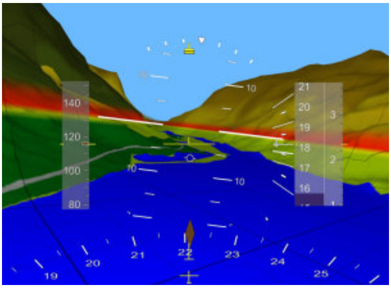
Airbus Helicopters’ RSAS and Leonardo’s OPLS offer a bi-modal HMI with visual and auditory cues, while the U. S. Army developed a tri-modal system with additional tactile cueing. The different modalities have their individual strengths and compensate for the weaknesses of the others. For instance, an auditory display can guide the pilot’s attention to a high-priority obstacle, whereas a visual representation provides a better overview of a complex multi-obstacle scene. The common approach is to show the situation via a 2-D orthographic top view on a head-down display. Such a view has distinct advantages over the natural egocentric view that pilots have from their seat: better view of important areas behind and on the sides of the helicopter, and more precise distance perception (no line of sight ambiguity, cf. Sec. 2.4.2). This explains why a conformal HMD symbology may not be the first choice for such scenarios. Nevertheless, HMDs can also integrate a 2-D top view, for instance in the form of a virtual instrument as developed in Chapter 5.

Figure 2.15b shows Leonardo's OPLS display with range rings, obstacle area visualization, and a colored beam indicating the direction and threat level of the closest obstacle. During low-speed maneuvering, the U. S. Army also uses a distance-based threat level computation like Leonardo and Airbus Helicopters [202]. For forward flight faster than 10 knots, they later introduced a speed-dependent threat space model based on time to collision [201]. Figure 2.16 depicts their display with caution and warning spaces for different speeds. Godfroy-Cooper et al. [112] showed that their isomorphic spatial visual-auditory display was favored over visual-only and audio-only representations. Further, a layered approach where cautions use visual and auditory cues, and warnings employ visual, auditory, and tactile cues was found useful [291].

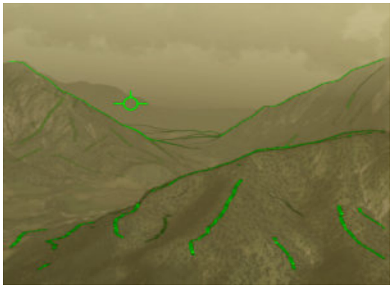
2.2.6.2 Terrain and Long-Range Object Visualization

CFIT and collisions with wires and other objects are prevalent causes of accidents during DVE operations [40, 219]. For low-altitude flights in adverse conditions, the pilots need a system that provides a proper picture of the surrounding terrain and potential hazards. The higher the forward speed, the more important become obstacles that are further away from the ownship.

Various terrain and obstacle databases with different resolutions and accuracies are available (see [323] for an overview). The common solution is to fuse the database information with real-time 3-D data from forward-looking sensors like lidar or radar. This approach can resolve database inaccuracies and incorporate hazards that are not stored in the database. Usually, the sensor data is processed in several ways before being displayed to the pilot. As a first step, lidar returns must be filtered. Then, they can be classified into ground and obstacle points, for instance via segmentation methods [59]. Later, the obstacles can be further grouped into specific types. Hensoldt distinguishes between poles, wires, trees, and unclassified objects [60]. Their long-range SferiSense 500 lidar, which is operational on the Finnish and German NH90 helicopter, detects 5 mm thin wires in 725 m distance (clear air) [212]. Besides being displayed, the processed terrain data can also be used by algorithms to find suitable spots for off-airfield landings [239, 297].



(a) Computer-generated terrain rendering on a head-down synthetic vision display with 2-D primary flight display overlay [213].

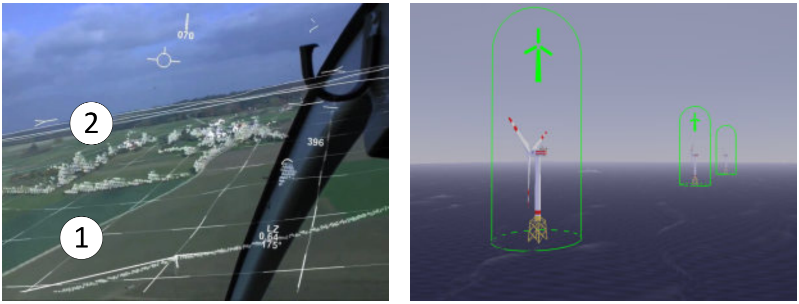


(b) Contour line and ridge/valley visualization conformally superimposed onto the degraded out-the-window view [58].

Figure 2.17 – Different terrain visualization approaches for head-down PMDs and see-through HMDs.

The visual representations of terrain and obstacles in flight guidance displays differ greatly, depending on the type of display that is used. A popular solution on PMDs is to integrate a color-coded terrain representation into the 2-D top-view navigation display [e.g. 23]. However, more interesting in the context of this thesis are 3-D perspective terrain visualizations with conformal obstacle symbology. They try to improve the pilot's situation awareness by reconstructing visual cues that are invisible due to the environmental conditions. Despite their common idea, 3-D terrain visualizations on PMDs and HMDs are very different. Symbology on a see-through HMD always wants to preserve the natural view of the environment. Its maxim is to highlight important features without cluttering the pilot's out-the-window view. By contrast, a PMD does not overlay with the natural view but generates a fully synthetic view.

Regarding PMDs, the literature provides useful guidance on how to choose database resolution, texturing, and shading for synthetic terrain displays [24, 270]. As visible in Fig. 2.20, the Integrated Cueing Environment (ICE) by the U. S. Army maps real-time infrared (IR) imagery onto the 3-D terrain data — an alternative to the synthetic texturing and shading known from classic SVS (Fig. 2.17a). A common approach for both PMDs and HMDs is to overlay the terrain with a conformal grid symbology [39, 97, 326] (see Figs. 2.17a and 2.18a). A regular grid improves the altitude perception because it provides splay and depression cues as the angle between grid lines in flight



(a) Terrain grid ① and shaded dot representation of non-ground lidar returns ② [326].

(b) Obstacle highlighting with DLR's glass dome symbology [237].

Figure 2.18 – Conformal terrain & obstacle symbology for see-through displays.

direction and the separation of the perpendicular lines change with aircraft altitude [97]. Da Silva Rosa et al. [45] found that a lower grid cell size caused better performance of the altitude control task during a terrain-following hill-climb. To avoid HMD clutter, the grid is often faded out in the near field [213, 323]. Alternatively, Eisenkeil [58] proposes a visualization of contour lines, ridges, and valleys as illustrated in Fig. 2.17b.

Detected obstacles are visualized in many different forms. A popular approach is the representation of non-ground lidar returns as shaded dots [294, 326]. Figures 2.18a and 2.20 show that this can generate a realistic and intuitive impression of the scene in certain scenarios. However, it will certainly obscure too much of the real obstacle in other situations. Therefore, a 3-D conformal hull in the form of a box [58, 146, 326] or a glass dome [235] is often drawn around the obstacle (see Fig. 2.18b). Even simpler is the placement of plain marker symbols to indicate poles, wires, or trees [330].

2.3 Symbology Overlays for the External Vision

The previous section showed how the pilot's out-the-window view can be replaced or enhanced by recreating the real world on a PMD or AR-HMD. This can already be enough to enable the pilot to safely fly the aircraft in DVE. However, often it is necessary or desired to provide supplemental information. This section gives an overview of state-of-the-art symbology that additionally supports the pilots in their aircraft control and navigation task. In contrast to their differences regarding terrain visualization, the aircraft state & flight guidance symbology does not differ largely between PMD- and HMD-based vision systems. It is always designed as an overlay over the synthetic or natural outside view. The section considers helicopter operations only.

2.3.1 Basic Aircraft Control

Often, the view of the environment is augmented with primary flight information. The idea behind that is to reduce the focus shifts between out-the-window view and instrument panel so as to make attention switches between real world and display domain easier. The simplest way to do this is to overlay the 3-D scene with a 2-D, see-through version of a conventional primary flight display (PFD). Figure 2.17a shows a head-down SVS with such a 2-D overlay. More advanced solutions try to better integrate the primary flight information with the far domain via scene-linking and conformal symbology [183, 238, 276]. For instance, Döhler et al. [49] implemented a conformal heading tape and horizon line. Further, Schmerwitz et al. [269] show how speed indications can be scene-linked in order to tackle the divided attention issues of AR displays.

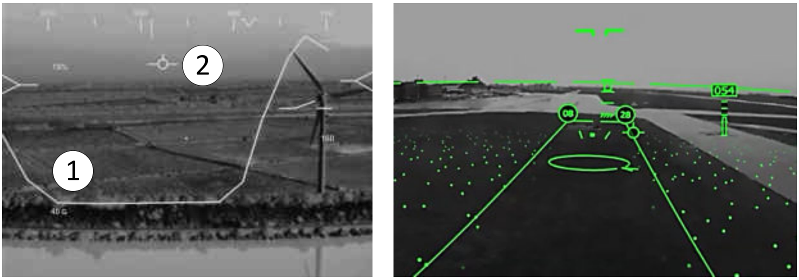
Additionally, the whole outside world visualization discussed above provides cues for the pilot to stabilize and control the helicopter. As summarized by Viertler [323], the pilot uses outside visual cues like optical flow, micro- and macrotextures, and several depth cues. This means that all other conformal symbology elements like terrain, obstacles, or synthetic flight guidance representations play a major role for the pilot stabilizing the aircraft.

2.3.2 Low-Level, Contour, and Nap-of-the-Earth Flight

Low-altitude flights are generally classified into three categories [220]: First, *low-level flight* is conducted close to the ground but above most obstacles, mostly level with up to maximum speed. Second, a pilot performing *contour flight* continually adapts the altitude to follow the contour of terrain and obstacles. Third, the most challenging type is *nap-of-the-earth flight*, where the helicopter flies very close to the ground, below the top of surrounding obstacles, e.g. through a forest aisle or river valley, usually to prevent detection by hostile defense systems. The lower the altitude, the more agile maneuvering and faster reactions are required by the pilot (and the aircraft). In such demanding operations, advanced flight guidance symbology can reduce the pilots' workload and enhance their situation awareness. As an addition to the bare visualization of terrain and obstacles, one can add various kinds of symbology to keep the pilots out of danger zones or guide them along the desired path. With regard to Parasuraman's [232] human-machine interaction model (see Sec. 2.2.5), this means that the information acquisition and analysis functions are highly automated and a suitable decision is suggested by the system. The final decision making and action implementation usually remain the job of the pilot; at least as long as current research on automatic trajectory following control is not considered [241, 299, 339]. The following symbol sets can be implemented on both PMD- and HMD-based vision systems.

Strict vertical and horizontal guidance along a desired path is usually realized via a flight director or a tunnel-in-the-sky display. The latter is probably the most famous conformal flight guidance symbology with a long history of innumerable variants — each providing different precision, another degree of display clutter, and varying attention capture (see [209] for an in-depth analysis). The literature reveals that a tunnel-in-the-sky improves flight path tracking [88, 173]. Additionally, a head-up presentation enhances the detection of *expected* events in the out-the-window view [87]. On the other hand, both head-up and head-down tunnel displays have been shown to impede the detection of *unexpected* and non-salient events [87, 88, 98, 173]. In a joint flight campaign, DLR and Hensoldt [357] demonstrated how data from the SferiSense lidar can be used to continuously monitor if the pre-planned tunnel is obstacle-free. If a hazard is detected, the DVE system initiates its online trajectory re-planning and adapts the tunnel to ensure obstacle clearance.

More restrictions lead to more workload for the pilot to follow the path. Thus, a narrow tunnel should only be used if precise path following is really needed. Several state-of-the-art solutions use terrain, obstacle, and ownship data to draw a so-called "safety line" [113, 238, 273]. This conformal line represents an intuitive way of showing the pilots if their predicted flight path is obstacle-free. As illustrated in Fig. 2.19a, keeping the flight path marker above the safety line ensures obstacle clearance. This allows for a largely unrestricted flight with an intuitive visualization of unsafe directions. Other less strict alternatives can be a wider tunnel-in-the-sky or Knabl's [147] route symbols, which are conformally drawn onto the ground (no vertical guidance).



(a) Safety line ① and flight path marker ② superimposed onto IR imagery [213].

(b) DLR's conformal HMD landing symbology with drift indication dots [268].

Figure 2.19 – Examples of conformal flight guidance symbology.

2.3.3 Hover and Landing[22]

Hovering and landing in DVE pose a major challenge for pilots as these maneuvers have high requirements on outside visual cues. A lack of these can lead to spatial disorientation, loss of separation to obstacles, and — in the worst case — crash landings like the typical brownout rollover [116]. To avoid this, specific hover and landing systems were developed as an addition to the pure external view representations introduced in Sec. 2.2.6. The "Rotary-Wing Brownout Mitigation" report [221] of the NATO Research and Technology Organisation gives a good overview of research conducted by various nations until 2011. This includes, for instance, the *Low Visibility Landing Aid* program in the UK and the DARPA programs *Sandblaster* and *Digital Backbone*. Also, research institutions like DLR [174] and several universities [12, 285, 323] joined the DVE mitigation efforts. Today, two of the most advanced developments are the SFERION™ system by Hensoldt [213, 215] and the various DVE systems that the U. S. Army implemented during the *DVE-M* program and its predecessors [106, 294–296].

A major difference between the landing symbologies is that the U. S. Army's ICE is originally designed for PMDs while Hensoldt and DLR specifically target HMDs.[23] This means that a pilot using the latter sees a (degraded)

[22] Parts of this section have been published by the author in [268].

[23] None of these uses PMDs or HMDs exclusively but the main focus regarding the landing symbology is placed on the mentioned display types.

natural out-the-window view overlaid with synthetic landing symbology as illustrated in Fig. 2.19b. By contrast, the ICE superimposes the symbology onto an egocentric 3-D perspective view of the surroundings based on fused data from various aircraft-mounted sensors and databases. Figure 2.20 shows this landing symbology during final approach to a confined touchdown zone.

Figure 2.20 – Landing symbology of the Integrated Cueing Environment by the U. S. Army [268]. The red and yellow dots represent classified lidar returns — in this case a captured power line.

All major systems have in common that they use conformal symbology to augment the natural or synthetic out-the-window view. Virtual frames around the desired landing spot and towers/boxes at the end of the touchdown area provide world-fixed references. These prevent spatial disorientation and allow the pilots to estimate their motion relative to the environment, which is masked by a moving particle cloud during brown-/whiteout. This is essential because a helicopter touchdown with a sideways velocity component can result in a dynamic rollover and hull loss. In addition to the fixed references, DLR's solution [268] uses a dynamic dot pattern to visualize the ownship drift via the pilot's peripheral FOV (see Fig. 2.19b).

It is important to note from Fig. 2.20 that the U. S. solution augments the synthetic view with a distinct, non-conformal overlay: an enhanced version of their BOSS display [292], which comprises aircraft state information and a 2-D top view for horizontal guidance (the white elements in the center and upper middle of the view). In other words, a 2-D plan view is overlaid with a 3-D egocentric view even though no direct visual connection between the two layers exists. This implies that the pilots have to mentally integrate the different kinds of information which are displayed in distinct frames of reference but still overlaid with each other in the same view. In contrast, the maxim of DLR's landing display is to visually fuse the overlaid symbology as best as possible with the scenery. All positioning guidance is integrated in a conformal way. For instance, a "rising deck" indicates height while virtual position markers on the ground guide the pilot to the desired touchdown position [268]. Further, DLR uses the proven scene-linking approach by presenting digital speed and height indications like road signs virtually erected at the far end of the touchdown zone (Fig. 2.19b).

A fundamental conceptual difference of the U. S. Army's ICE compared to DLR's and Hensoldt's symbologies is its higher level of automation regarding information analysis and decision selection (cf. Parasuraman's model in Sec. 2.2.5). Both Hensoldt's and DLR's philosophy is to enhance the degraded out-the-window view such that the pilots can safely fly the aircraft with a low automation level[24] like they usually do in visual meteorological conditions (VMC). By contrast, the U. S. Army developed sensor-driven algorithms to compute an optimal approach path and uses extensive cueing to guide the pilot along that [294, 296]. As can be seen from Fig. 2.20, the two-dimensional BOSS part of the display presents the target vertical speed by means of a rounded magenta rectangle. Moreover, the top-down navigation layer shows recommendations for heading (magenta symbol on heading tape) and for horizontal velocity (magenta semicircle). It is the pilot's task to bring the horizontal velocity vector (white line) and the vertical speed indicator in line with the target cues. During the exemplary approach in Fig. 2.20, the green fill of the target symbol signals proper vertical speed while the horizontal velocity is slightly off target. Both approaches have advantages and drawbacks. The U. S. Army solution will probably result in a more predictable and precise

[24] Despite enabling manual flight, the performance with these symbologies was still found to be improved with higher automation levels.

maneuver; however, the symbology may cause attentional tunneling and requires specifically trained pilots. Further, the system itself is very complex.

The ICE displayed on a PMD has been shown to provide all necessary cues for the trained pilot to safely land the helicopter without out-the-window view. In a sense, it is used like an IFR display. For this thesis, it is important to note that several evaluation flights were successfully flown with completely masked cockpit windows solely based on the PMD symbology [294]. Recently, even an automation of the action implementation function was demonstrated in hands-off autonomous landing evaluations [298]. Thereby, the ICE became a monitoring display instead of a flight guidance symbology.

2.4 3-D Perspective Views in Flight Guidance Displays

A closer look at modern vision displays reveals that — depending on their purpose — these instruments present the current situation from various viewpoints and angles. The investigation of different perspective views in the context of a virtual cockpit will play an important role in this dissertation. Therefore, this section gives a structured overview of the various view formats, reviews their individual advantages and limitations, and lists current applications. This theoretical background forms the basis for the integration of a 2-D virtual obstacle display in Chapter 5 and for the VR-based 3-D ego- and exocentric flight guidance displays developed in Chapter 7.

2.4.1 Types of Ego- and Exocentric Views

Figure 2.21 provides a classification of the representation types that are most relevant in the context of this thesis. Some of them are very common and can be found in every modern flight deck. Others are rarely seen in aviation but might be interesting options for the future. A literature search delivers many terms describing the properties of such display formats. Often, the used terminology varies between research groups and communities. Thus, the graph should serve as a reference for the terminology employed by this work.

2.4.1.1 Classification of View Types

As illustrated in Fig. 2.21, the representations can be classified based on three parameters: 1) projection type, 2) viewpoint location, and 3) frame of reference. The projection type defines how the three-dimensional (3-D) real world is mapped onto the two-dimensional (2-D) display screen. The second parameter states where the viewpoint is located. In computer graphics terminology, the viewpoint is often referred to as the position of the camera, which shoots the image to be displayed. Finally, the viewpoint's frame of reference determines how the camera moves relative to the own aircraft. In combination, this makes six common display formats, which are discussed here in detail.

The projection type divides the display formats into two major groups: 3-D perspective views and 2-D orthographic views. The former use a one-point perspective projection with the projection lines converging at the viewpoint. This type of projection works similar to how the human eye perceives its surroundings. Thus, the resulting image looks realistic: Distant objects appear smaller and all lines that are perpendicular to the projection plane converge in one point at the horizon, even though they are parallel in the real world. A picture of a runway taken during final approach is an example of that phenomenon. In contrast, the orthographic views apply an orthographic projection, which implies that the projection lines are parallel and perpendicular to the image plane. Such projections are often seen in technical drawings because — compared to perspective projections — they better preserve the geometric properties of the object pictured.

A flight deck usually features orthographic displays with the viewpoint located in the environment, above the ownship (display format ⑥ in Fig. 2.21/2.22). This setup results in the well-known top-view navigation displays, sometimes called "god's eye view". However, this view can only show the horizontal plane of the three-dimensional situation. Thus, it is usually complemented by an elevation or profile view where the camera is positioned at the side of the aircraft so as to add the missing information about the vertical dimension. Such 2-D formats are often referred to as co-planar view [345]. Regarding the frame of reference, the camera follows the translational movements of the aircraft. The camera's pitch and roll orientation is aligned with the principal axes of the world frame in order to provide the plan top and side views. Yaw-wise the camera is either coupled to the ownship heading/track ("heading-/track-

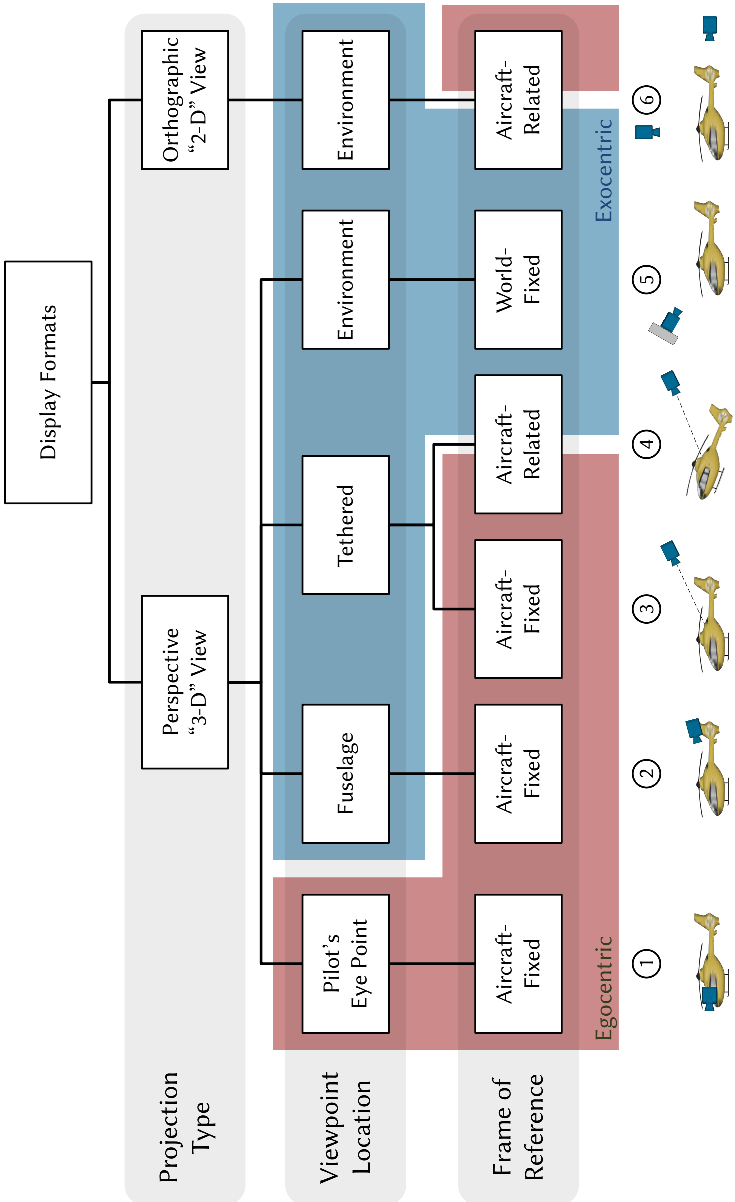


Figure 2.21 – Overview of view types used in flight guidance displays. The resulting images are illustrated in Fig. 2.22 (own illustration).

up mode”) or has a world-fixed direction towards north (“north-up mode”). Here, this combination of aircraft-fixed and world-referenced parameters is called “aircraft-related” frame of reference.

The 3-D perspective views can be classified into five groups based on their viewpoint location and frame of reference. In Fig. 2.21, the resulting display variants are represented by ① – ⑤. Figure 2.22 illustrates how the resulting images for the pilot look like. First, the virtual camera can be placed at the pilot’s real viewpoint, the eyes. For this variant, the aircraft-fixed frame suggests itself because it is the natural way how pilots perceive their environment. The pilot’s viewpoint is inherently coupled to the translations and rotations of the ownship. In summary, display format ① replicates the pilot’s natural out-the-window view. Wickens [343] calls this “immersed view”.

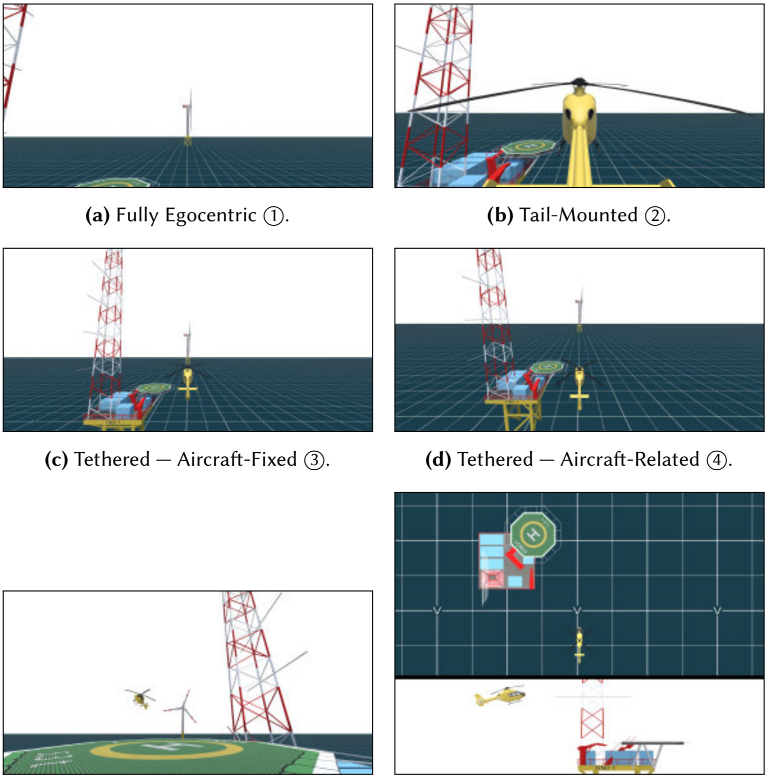
In option ②, the viewpoint is moved out of the cockpit to another location on the fuselage. This could for instance be the tail fin or the nose. Modern aircraft like the Airbus A380 and the Airbus H160 helicopter feature tail-mounted cameras providing the pilots with a view of ownship and near surroundings.

A “tethered view” [343] has a viewpoint that is not directly attached to the ownship but is still linked to it. Commonly, the viewpoint is positioned to show the own aircraft from behind and above. One can imagine the virtual camera being pulled behind the aircraft as if it was coupled via a tether or stick. Depending on the degree of this coupling, the aircraft-fixed format ③ and the aircraft-related option ④ are distinguished. In the former variant, the tether is rigid, which means that the camera moves whenever the aircraft attitude changes. As the viewpoint is “mounted” on a virtual lever arm, a pitch-up rotation — for instance — makes the viewpoint translate downward. Variant ④ avoids this by removing the linkage to the aircraft’s pitch and roll rotations. The camera follows only the translational movements and the yaw rotation of the aircraft. The camera’s pitch and roll angles are then stabilized relative to the world-fixed frame of reference.[25] Another option is a dynamic coupling via a mass-spring-damper system [33], detailed in Sec. 2.4.3.

View type ⑤ comprises a viewpoint located somewhere in the environment around the helicopter. It is world-fixed, implying that the camera pose is

[25] Further comparison of both options is made during the development of a tethered virtual cockpit view in Sec. 7.1.2.

not connected to any aircraft movements. A display that shows the situation as seen from the desired landing area is a possible example of such a representation.



(a) Fully Egocentric ①. **(b)** Tail-Mounted ②.

(c) Tethered — Aircraft-Fixed ③. **(d)** Tethered — Aircraft-Related ④.

(e) Environment ⑤. **(f)** Co-Planar ⑥.

Figure 2.22 – Resulting 2-D and 3-D views corresponding to the six representation types introduced in Fig. 2.21. All images depict the same situation, aircraft position, and attitude. Only the view type is changed (own illustration).

2.4.1.2 Ego- and Exocentrism

Talking about 3-D perspective views, the terms “egocentric” and “exocentric” are often used. Frequently, the whole representation is called like that. However, this thesis wants to emphasize that both the viewpoint and the frame of reference can be ego- or exocentric respectively. Figure 2.21 shows the classification of the six discussed display formats into these categories. A viewpoint is called egocentric if it is positioned where the pilot’s eyes are located in the real world. All other viewpoints are exocentric. Likewise, an aircraft-fixed frame of reference is termed egocentric whereas its world-fixed counterpart is exocentric. An aircraft-related frame of reference is a mixture of both. For example, the virtual camera in variant ④ follows the aircraft position and yaw (egocentric) but has a world-referenced pitch and roll orientation (exocentric).

From Fig. 2.21 it is obvious then, that a display format as a whole can be a mixture of ego- and exocentric features. Between the fully egocentric representation ① and the pure exocentric displays ⑤ and ⑥ (in north-up mode) is a wide range of compound variants. Wickens et al. [349] speak of “degrees of ego- and exocentrism” in that matter. Further, Wickens and Prevett [351] state that “greater egocentrism is created by perspective viewing, map rotation, and viewpoint positions that correspond to the axis of control”. Wang and Milgram [334] proposed a “centricity continuum” to account for the smooth transition between fully egocentric and completely exocentric views. In that paradigm, a tethered view ranges in the middle, combining ego- and exocentric characteristics.

Egocentric and exocentric perspectives are sometimes also termed “inside-out” and “outside-in view” respectively [344]. The former suggests that it shows the scene as if the pilots look from *inside* the cockpit *out* at the environment. Sitting in the cockpit, the aircraft remains at the same position relative to their viewpoint; the world moves relative to this aircraft-fixed frame of reference. The artificial horizon in a PFD is probably the purest form of such an inside-out display: Its aircraft-reference symbol always stays at the same position on the screen, while the simplified blue and brown world rotates around it.

Other common names for ego- and exocentric representations include “first-person” and “third-person view”. By the same token, a tethered view is sometimes called “second-person perspective”, which nicely highlights its position in middle between the two extremes. Finally, one should note that the term "(3-D) exocentric display" is often used as a synonym to tethered view; probably because it is the most common realization of an exocentric 3-D perspective [e.g. 101, 308, 342].

2.4.2 Advantages and Limitations of 3-D Views

The literature provides extensive research on the advantages and limitations of the various view types. Wickens [343, 345] sums up the results of many previous studies and compares the three major formats: 3-D immersed or egocentric (①), 3-D tethered (③/④), and 2-D co-planar (⑥). Table 2.1 shows the benefits and limitations he discovered. His comparison is based on six information processing mechanisms, which are listed in the first column.

First, Wickens argues that 2-D co-planar displays impose a high cost of visual scanning since the vertical and lateral information must be collected from two displays [343, 345]. Also, the cognitive integration required to process the information from two plan views is higher than with 3-D representations, which contain all three dimensions in a single picture. Third, 2-D formats violate Roscoe's principle of pictorial realism [257], whereas both 3-D variants are in line with this fundamental display design principle. A 3-D representation looks more realistic than a 2-D co-planar projection, which makes it easier to understand and to create a mental picture of the environment.

Regarding the remaining three information processing mechanisms, Wickens [343, 345], however, found several limitations of the 3-D representations. First, he argues that if the task requires only information from either the horizontal or the vertical plane alone, then the 2-D co-planar format is superior. For instance, an entirely lateral maneuver with no vertical information requirements appears to be easier with a plan map view than with a 3-D perspective view. Second, a well-known weakness of perspective views is the so-called line of sight (LOS) ambiguity. It means that the exact location of an object along the LOS axis can hardly be determined in such a projection. McGreevy and Ellis [185] showed the negative influence of this ambiguity on direction judgments. According to Wickens, this cost is even doubled in a 3-D exocentric view as both ownship and target location are hard to assess. This weakness is immediately visible from Fig. 2.22c–e where the exact position of the helicopter relative to the landing platform is impossible to assess. Finally,

Table 2.1 – Costs and benefits of different representation formats according to Wickens [345] (Used with permission of Taylor & Francis Group, conveyed through Copyright Clearance Center, Inc.).

	3-D		2-D
	Immersed	Tethered	Co-Planar
Cost of scanning	low	low	high[a]
Cost of cognitive integration across planes (axis pairs)	low	low	high[a]
Principle of pictorial realism	confirmed[b]	confirmed[b]	violated
Requirement of focused attention on an axis or plane (axis pair)	violated	violated	supported
Line of sight ambiguity	cost[c]	double cost[c]	
Keyhole view	cost[d]		

[a] Increased with greater physical separation between lateral and vertical display panels.
[b] Less benefit at higher altitudes.
[c] Cost is decreased with more depth cues.
[d] Cost is decreased with larger geometric field of view.

an immersed 3-D view creates a keyhole view because the observer cannot see objects that are beside, below, above, or behind the ownship. For example, the landing pad and the obstacle are mostly outside of the FOV in Fig. 2.22a. Of course, this issue could be diminished by enabling the pilot to interactively change the viewing direction of the display. However, this would increase the scanning cost mentioned above.

The comparison reveals that each view type comes with individual strengths and weaknesses. To decide which display to use when on the flight deck, these general characteristics must be evaluated in the context of a concrete flight task. A widely accepted opinion is that such displays should serve two aspects of the pilot's spatial orientation needs: 1) local guidance and 2) global awareness [166, 184, 255, 337, 349]. Local guidance includes the support of the pilots in controlling the aircraft and following the desired flight path. Global awareness comprises information about the situation in a wider spatial and temporal context. For instance, the pilots must know their own position relative to obstacles, traffic, and other hazards. Being globally aware also means having a mental picture of how to reach the destination or more generally how to fulfill the mission task.

In summary, the available literature indicates that greater egocentrism supports local guidance. On the contrary, global awareness is minimal on the egocentric side of the centrism continuum and increases with greater exocentrism. For instance, Wickens [344] states that “flight control (tracking accuracy) is much better with an egocentric view, but [...] noticing hazards in the airspace (referred to as level 1 spatial awareness) and understanding their general location (level 2 spatial awareness) are better served by a more exocentric view”. Several references to task-specific studies are provided by [343, 345]. For example, flight path following — a classic control task — was found most precise with an egocentric tunnel-in-the-sky symbology [126, 351]. In terms of Wickens’ six information processing mechanisms, this is explained by the integration of all three spatial dimensions into one display. Compared to an exocentric 3-D display, the LOS ambiguity of the egocentric 3-D display is lower because at least the position of the ownship is known precisely (center of the display) [343].

Since a tethered view combines an egocentric reference frame with an exocentric viewpoint, it was found to offer effective local guidance for manual control tasks [255, 334]. Compared to a fully egocentric view, it offers a superior preview range. This characteristic makes tethered views an interesting choice whenever a compromise between local control and global awareness is required: for example, when the pilot should be able to control the aircraft but still be more aware of the environment than through the keyhole of an egocentric view. This approach is taken by the author in Chapter 7.

In summary, Wickens’ work shows that no single best representation exists. Each comes with advantages and drawbacks. Thus, it is recommended to analyze the flight task that should be supported by the display and choose the representation type which fits best. In addition, one can provide multiple views that complement each other as well as enhance the pure display formats to weaken their drawbacks [345]. The most famous example of the latter approach are probably artificial “droplines” for exocentric views [e.g. 185, 349]. These are drawn vertically from an object to the ground in order to mark its position in the horizontal 2-D plane. This reduces the ambiguity of 3-D positions in perspective views. Another example is Olmos’ [228] work on enhanced symbologies fixing ambiguities and other issues in 3-D perspective displays. The author will also follow this approach during the development of the 3-D perspective views for a virtual cockpit (see Sec. 7.1).

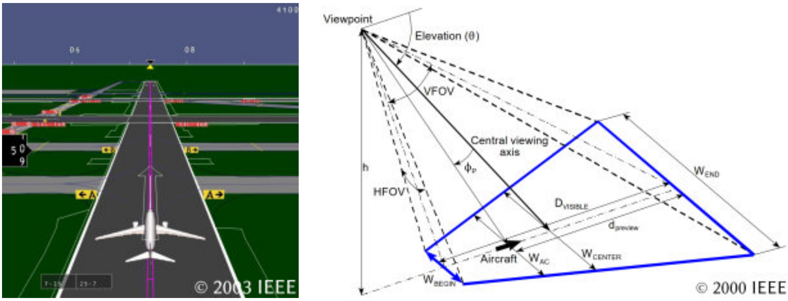
2.4.3 Applications of Tethered Views for Flight Guidance

Exocentric perspective display formats have been investigated extensively in the context of head-down synthetic vision displays. Primarily, they have been used to guide pilots during taxiing and terminal area operations (approach, departure). Several researchers tried to optimize the parameters of tethered views and compared the novel representations with the established 2-D coplanar and 3-D egocentric displays. Today — many years after the first research studies on synthetic vision displays — every modern avionics suite offers synthetic views in various formats and with several colorful overlays showing guidance symbology and highlighting hazards [197]. This section presents notable research and exemplary applications of tethered views which are relevant for the development of the author's virtual cockpit.

Taxi Guidance Displays About 25 years ago, Foyle et al. [102] developed NASA's Taxiway Navigation and Situation Awareness system (T-NASA). It enhances the natural out-the-window view with a scene-linked HUD symbology and complements this egocentric view with an exocentric/tethered 3-D perspective on a head-down moving map display. In this combination, the egocentric view provided local guidance while the exocentric display aided global awareness. This resulted in improved taxi performance under low visibility conditions [184].

Later, Theunissen et al. [309] followed a different approach to reducing the dependence on the out-the-window view during surface operations. As common, they used a 2-D top-view surface navigation display for global awareness. However, their novel idea was to also use an exocentric display for local guidance. In contrast to the exocentric displays providing global awareness, their additional local guidance display was a tethered view at a higher zoom level. As illustrated in Fig. 2.23a, it did not show a wide-range overview from high above the aircraft (like a navigation display). Instead, it depicted the ownship on the taxiway from a viewpoint close behind and above. DLR's TARMAC-AS display [172] offers similar perspective views for taxi guidance.

The main advantage of 3-D perspective displays is their integration of the three spatial dimensions into one representation. Thus, it does not seem obvious to apply such a format to surface operations — a 2-D task. Theunissen et al. [310], however, argue that their tethered view is favorable anyway because it combines a high position resolution near the ownship with a sufficient preview



(a) Tethered view presented on a head-down PMD [310].

(b) Illustration of the design parameters involved in defining this view format [308].

Figure 2.23 – The exocentric surface guidance display by Theunissen et al.

range. Finding a suitable trade-off between these two essential attributes is a hardly solvable problem for other display formats. In a 2-D plan view, one can increase the position resolution by zooming in. However, this reduces the display/preview range, which is required to orientate oneself. By contrast, in Theunissen's display, shown in Fig. 2.23a, the pilot can accurately estimate the aircraft position relative to the taxiway but still have an adequate preview of the route ahead.

A notable aspect of Theunissen's work is the in-depth analysis of the parameters involved in the definition of such a tethered view [307, 308, 310]. This presents a valuable source for designers of exocentric displays for different use cases. Figure 2.23b illustrates how the resulting viewing area (blue trapezoid) depends on the design parameters viewpoint position, viewing direction, and FOV. The literature review presented in [310] reveals that a wide range of values for these parameters have been tested and that their optimum highly depends on the target scenario and task. For their specific surface operations, Theunissen et al. [310] chose a FOV of 53° and an elevation offset Φ_P of 15°. In a simulator study, they further confirmed that 100 m distance between viewpoint and ownship together with an elevation angle θ of −30° appears to be "close to optimal" for their scenario [255, 310]. This author will determine its own view parameters optimized for helicopter operations in Sec. 7.1.

Navigation Displays Tethered views are also often seen in navigation displays, especially for approach and departure guidance in mountainous regions. Prevett and Wickens [244] summed up the early research in this context. They found evidence that 3-D exocentric views provide better spatial awareness while the egocentric perspective is preferred for better tracking performance. Later research includes NASA's multi-mode navigation display, which combines a 2-D co-planar and a 3-D exocentric view. Prinzel et al. [246, 247] showed that their novel display significantly improves situation awareness when presented together with an egocentric synthetic vision PFD. For instance, the airliner pilots reacted much earlier to an impending CFIT in their simulator experiment. Similarly, Ebrecht and Schmerwitz [55] presented a concept for various exocentric 3-D views combined with a 2-D profile view in the navigation display. This synthetic vision display was enhanced with overlaid symbology highlighting the desired flight path and hazards like adverse weather zones [56].

Dynamic Tether Colquhoun and Milgram [33] argue that a rigid tether violates the motion compatibility principle because the pilots visually experience a motion opposite to their input. For instance, commanding a left turn makes the viewpoint, which is mounted onto a virtual lever arm behind the aircraft, move to the right. Also, this camera translation increases with tether length. To address this issue, they propose a dynamic tether modeled via a mass-spring-damper system. Follow-up studies by Wang and Milgram [335–337] found that an "intermediate" tether length and a critically damped system induced the best performance in a trajectory following task through a tunnel-in-the-sky. However, no significant performance differences between rigid and dynamic tethers were observed even though the dynamic tether was preferred by subjective ratings [334]. This finding was later confirmed by Hollands and Lamb [131] who found no effect of dynamic versus rigid tether for remote vehicle operations in complex terrain.

2.5 Recapitulation

The dissertation proposes a virtual cockpit, which uses an HMD to immerse the pilot into a computer-generated external view augmented with virtual instruments and flight guidance symbology. For each of these building blocks, this chapter provided basic knowledge, explained details, and reviewed the status quo of fielded systems and ongoing research. In summary, the key points are:

- A wide range of HMDs — from optical via video-see-through to fully opaque devices — is available, each coming with very different characteristics, qualities, and limitations. Optical AR-devices always superimpose the natural view, whereas video-see-through HMDs allow a selective combination of real and virtual, and fully opaque goggles generate an entirely virtual world.
- Vision systems — which re-create the degraded out-the-window view via sensors and databases on a display — become increasingly available, even though they "only" create situation awareness but no operational benefits so far (except specific EFVS).
- Research on helicopter DVE mitigation shows that aircraft-mounted sensor suites can increase the safety in confined area operations; they even proved to enable landings with no natural outside vision.
- Visualization techniques for terrain and obstacles differ greatly between transparent HMDs and opaque PMDs. A virtual cockpit using an opaque HMD should combine the relevant ideas from both types and augment these with the proven scene-linked and conformal symbology.
- Tethered 3-D views have several advantages, which may be interesting for flight guidance in fully immersive HMD views.
- Several concepts and visions for HMD-based future cockpits exist but only few concrete implementations and practical evaluations were found in the literature.

Chapter 3

Virtual Cockpit Concept

This chapter describes the conceptual framework of the thesis: the author's concept of an HMD-based virtual cockpit. The first section addresses research question 1-A[1] with the development of a virtual cockpit taxonomy. Thereafter, the author elaborates on the potentials of a virtual cockpit and discusses the challenges on the way to implementing such an approach. This second part provides answers to RQ 1-B. Finally, the theoretical framework is applied to helicopter offshore operations, which forms the basis for the concrete implementations of a virtual cockpit in the Chapters 5–7.

3.1 Variations of a Virtual Cockpit

As described in the introduction, the author started his work with the idea of using a non-see-through HMD in the cockpit (see Fig. 1.3). The resulting "virtual cockpit" should replace (or at least expand) the existing cockpit displays and thereby overcome their limitations. Over time, this first idea turned into a multifaceted approach; which finally means that there will be *no single* concept of *the* virtual cockpit. Instead, the author sketches multiple variants between a conventional and a fully virtual cockpit.

[1] The research questions were posed in Sec. 1.3.2.

3.1.1 The Virtual Cockpit Continuum

To illustrate the different variations of a virtual cockpit, the author devised the "virtual cockpit continuum" sketched in Fig. 3.1: It extends from a conventional cockpit on the left via several types of partially virtual cockpits in the middle to a fully virtual cockpit on the right. This continuum represents an advancement of Milgram's general reality–virtuality continuum (see Sec. 2.1.1); it applies his theoretical thoughts to the author's specific use case of a cockpit.

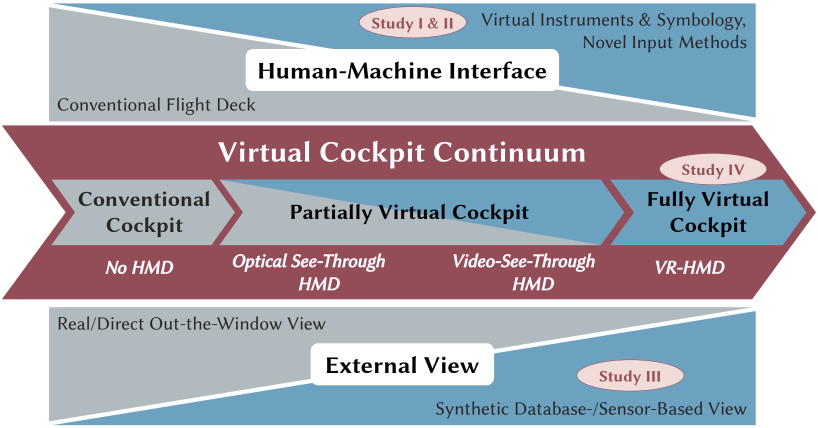


Figure 3.1 – Virtual cockpit continuum — a schematic illustration of the broad range of cockpit types, from conventional via partially virtual to fully virtual. From left to right, the conventional elements decrease while the virtuality increases in both domains of the cockpit (human-machine interface & external view). Fig. 3.2 shows exemplary visualizations of the various stages. The red ellipses indicate the focus of the author's studies in Chapters 5–7 (own illustration).

The upper and lower rectangles in the graph show that the author's notion of "cockpit" comprises two domains: 1) the human-machine interface (HMI) and 2) the external view. In case of a conventional cockpit (here in gray) the two domains are represented by a traditional flight deck and a real/direct out-the-window view as seen in Fig. 3.2a. The other extreme — a fully virtual cockpit, visualized in blue — has no physical instrument panel but only virtual instruments & symbology generated by a VR-HMD as well as novel input methods to interact with the new cockpit. Also, the direct view of the surroundings through the cockpit windows is replaced by a computer-generated HMD view, which is made of pre-stored and live-sensed data. This undoubtedly drastic approach reflects the above-mentioned initial idea which started this work: a straight VR-based cockpit. Figure 3.2d shows the author's implementation of such a cockpit, as it is developed in Chapter 7. Its only physical HMI are the flight controls.

Between these extremes, many intermediate types of partially virtual cockpits exist. The gray-to-blue color transition in Fig. 3.1 illustrates that the conventional elements decrease in both domains from the left to the right. Concurrently, virtual symbology and synthetic external view become more important. The review of current research in Chapter 2 shows that state-of-the-art DVE systems already include a certain degree of virtual symbology and synthetic external views. This is achieved by using optical see-through HMDs in otherwise conventional flight decks. As illustrated in Fig. 3.2b, the standard cockpit HMI is extended by HMD symbology like a head-up PFD and other flight guidance symbol sets. Also, the real out-the-window view is commonly augmented with overlaid sensor imagery or conformal terrain and obstacle representations (see Sec. 2.2.6 and 2.3 for details).

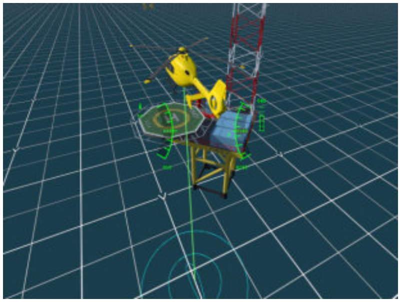
Moving further right in the continuum, the importance of the conventional cockpit elements further decreases. Information that is conventionally presented on PMDs is now moved to the HMD, for instance in the form of novel virtual cockpit instruments (see Chapter 5). The farther right in the continuum, the more important becomes the ability to not only augment the reality but to also "cut out" certain parts of the reality and replace it by pure virtual content. For instance — instead of only showing overlaid symbology — the natural out-the-window view might be fully replaced by an entirely synthetic representation. On the other hand, the pilot may still want to see parts of the conventional flight deck; only the extents of the windows and of sight-blocking aircraft structures should be replaced by the virtual view. Such a partially virtual cockpit can be realized with video-see-through HMDs, which allow for a selective combination of images from the HMD-mounted cameras with a computer-generated external view. Figure 3.2c shows how this may look like through the pilot's eyes.

The virtual cockpit continuum expands the initial idea of the thesis as it presents different degrees of "cockpit virtuality", from conventional via par-

(a) Conventional cockpit.

(b) Partially virtual cockpit with optical see-through HMD — A head-up PFD symbology augments the pilot's natural view.

(c) Partially virtual cockpit with video-see-through HMD — A video stream of the conventional display panel is integrated into an otherwise virtual view.



(d) Fully virtual cockpit — The pilot sees a completely computer-generated view. Here, an exocentric display of the ownship. This is developed in Chap. 7.

Figure 3.2 – Exemplary illustrations of the pilot's view at various stages of the virtual cockpit continuum (cf. Fig. 3.1). Note that all pictures show exactly the same situation but the two most virtual variants provide significantly more information about the surroundings: a computer-generated external view with additional visual cues, no occlusion of the landing pad by the aircraft structure, and no reduced visibility. Details are explained later in Sec. 3.2.2 and Chap. 6 & 7 (own images).

tially to fully virtual. An essential aspect hereby is the type of HMD used. Thus, Fig. 3.3 compares four common HMD designs with regard to how they visually combine the real and the virtual parts of the environment (technical details see Sec. 2.1.2.3). The presented HMDs are sorted according to their degree of virtuality; farther right means higher virtuality — as in the continuum. Since current displays do not cover the whole human visual field, one has to distinguish two parts of the pilot's FOV: the inner part, which is covered by the actual display area, and the outer part surrounding the virtual image.

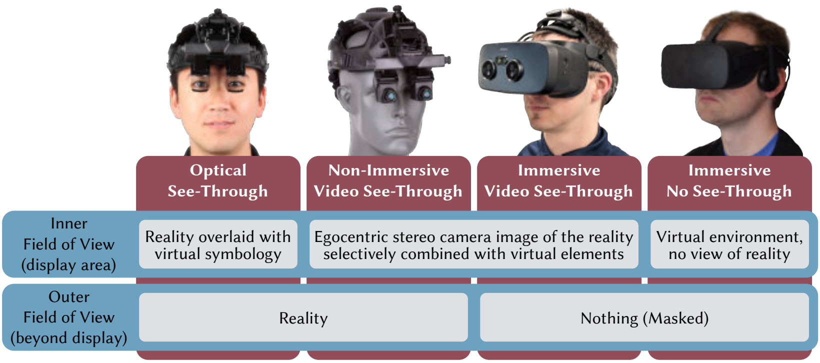


Figure 3.3 – Comparison of how pilots see the real and the virtual environment when wearing different HMDs (own illustration, images from [26]).

With a classic optical see-through HMD, the reality remains in sight throughout the pilot's whole visual field.[2] One can only *add* virtual objects to the natural real-world view, which itself cannot be influenced. Despite this limitation, it allows the virtualization of certain cockpit elements, which is demonstrated in Chapter 5 with so-called virtual instruments. This reflects the lowest degree of cockpit virtuality.

By contrast, video-see-through HMDs block the direct real-world view in the display area and replace it with a conformal live video stream, generated by two HMD-mounted cameras. This design makes it possible to electronically enhance or generally adapt the image and further allows the occlusion of real objects with computer-generated content [26]. Such HMDs support the

[2] Minor parts of the reality may be occluded by the visor framing and the view through the visor can distort the reality slightly.

above-mentioned idea of selectively combining real and virtual environments, which is crucial for setups in the right half of the virtual cockpit continuum. At this point, it is important to note that the stereo camera view does not cover the pilot's whole FOV, which leads to two distinct designs with regard to what is visible in the peripheral areas: Non-immersive designs like SA Photonics' SA-62/E [26] allow the pilots to simply see the real world around the display because they do not obscure these areas. Immersive designs like the Varjo XR-3 [319], on the other hand, mask the whole area between display and face with a box-shaped housing. For the virtual cockpit design, this means that one can choose between a direct peripheral real-world view or no peripheral view at all. Both options have advantages and disadvantages depending on the intended function.

The last HMD variant in Fig. 3.3 are the typical VR goggles: fully immersive, with no direct or camera-based see-through capability. These properties fit with a fully virtual cockpit where no physical flight deck or other parts of the reality must be directly visible. The whole environment — HMI and external view — is computer-generated. Nevertheless, one can still show video data from aircraft-mounted sensors (details in the next section).

3.1.2 System Overview — Partially & Fully Virtual Cockpit

Figures 3.4 and 3.5 elaborate the concept of a partially virtual cockpit, situated in the middle of the continuum, and a fully virtual cockpit, the right pole of the continuum. They provide a more detailed sketch of the system structure, the different view domains, and the flow of the visual data to the pilot's eyes. Consistent with the virtual cockpit continuum, the graphs are divided into two major domains: 1) *external view* on the left, and 2) *human-machine interface* on the right. Note that the input from the pilot to the system is only sketched roughly because it is not the focus of this work. Section 3.3.2 discusses various options for pilot interaction in a virtual cockpit.

The major differences between partially and fully virtual cockpit are the HMD type and the view domains that are displayed to the pilot. In a partially virtual cockpit, both HMI and external view have a computer-generated and a natural view domain respectively. By contrast, the fully virtual cockpit only has the computer-generated view domains, visualized in blue.

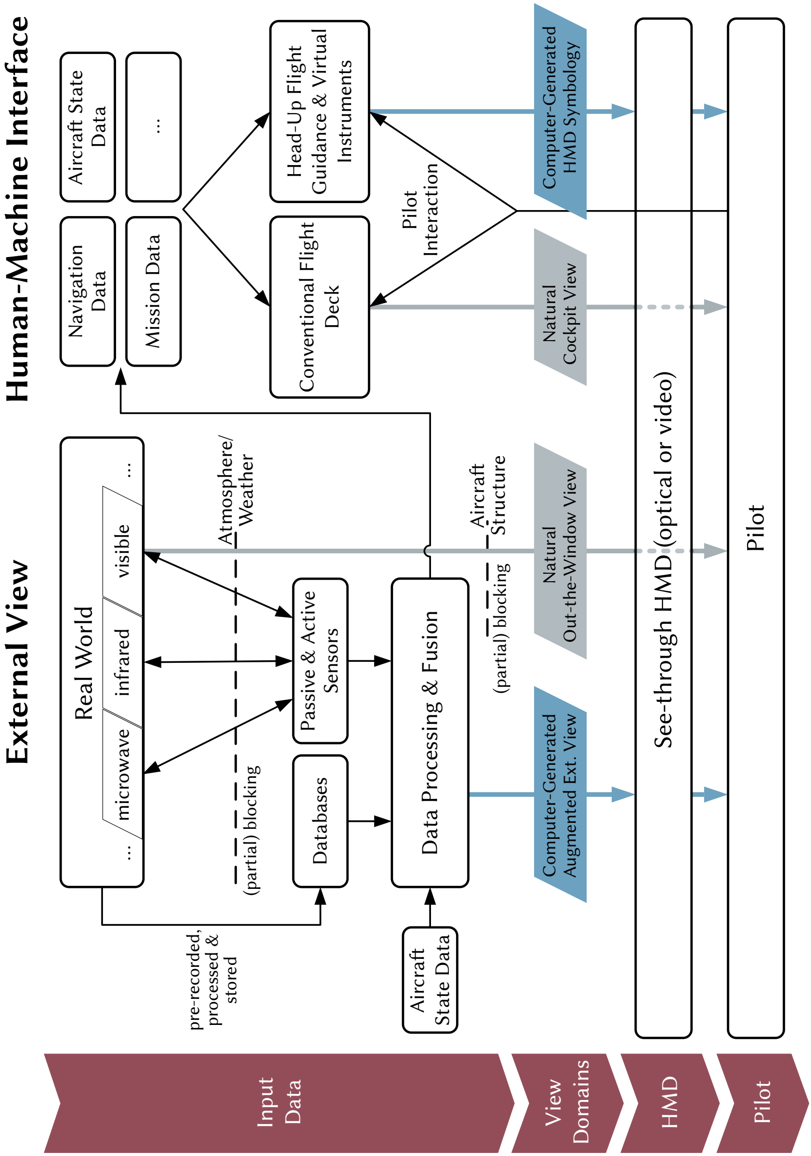


Figure 3.4 – Partially virtual cockpit — view domains (gray and blue rhomboids) and general system structure (own illustration).

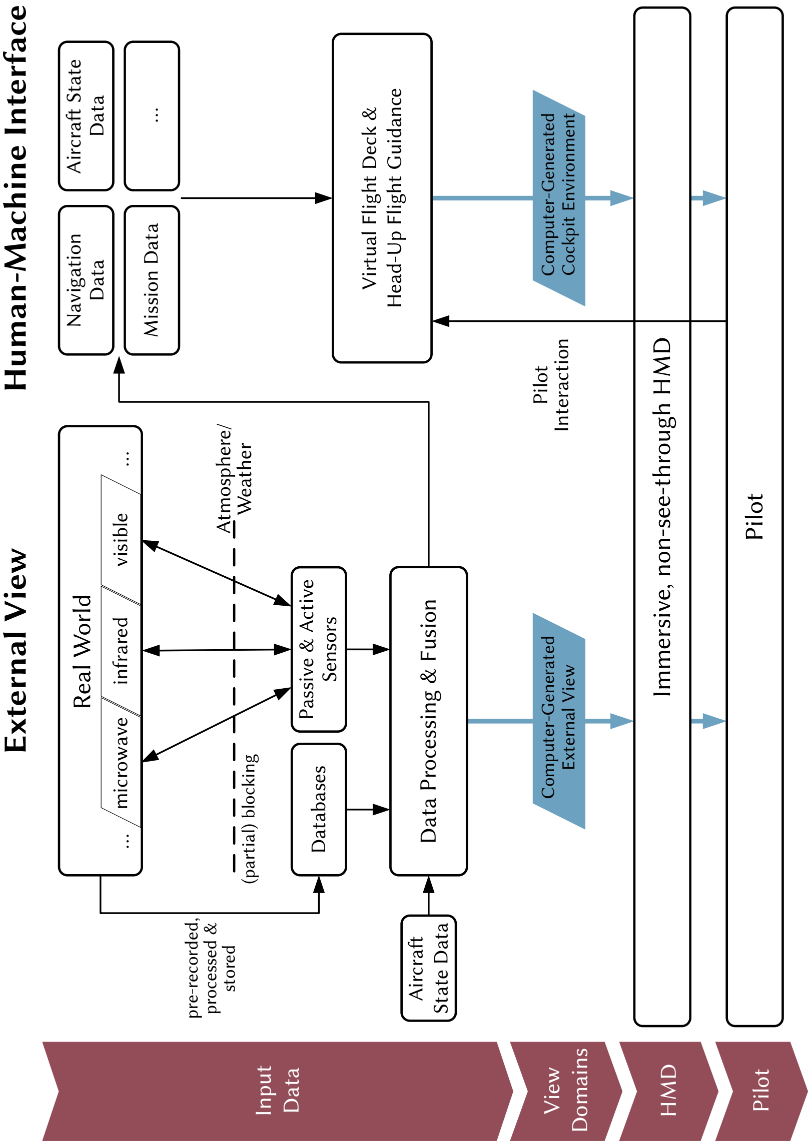


Figure 3.5 – Fully virtual cockpit — view domains (blue rhomboids) and general system structure (own illustration).

For the external view, both variants build on the state-of-the-art vision systems introduced in Sec. 2.2. They use at least a class 2 DVE system as specified by the NIAG (see Fig. 2.13). Aircraft-mounted passive and active sensors capture the real world over various ranges of the electromagnetic spectrum, from the microwave via the infrared to the visible region. As detailed in Sec. 2.2, the combination of sensors working with different wavelengths is essential because one sensor can then compensate for weaknesses of the other (e.g. range, resolution, or attenuation for certain particle sizes in the atmosphere). The sensor data is processed and fused with pre-stored database information on terrain, obstacles, et cetera. The final result is a computer-generated external view. In a partially virtual cockpit, the optical or video see-through HMD combines this artificial representation with the pilot's natural out-the-window view, which is limited to the visible spectrum and partially blocked by the aircraft structure and atmosphere/weather (i.e. DVE). A fully virtual cockpit only has the artificial view domain.

The HMI side of a partially virtual cockpit features a conventional flight deck that is directly seen by the pilot through the combiner or via the stereo cameras of the HMD. This view domain is called the natural cockpit view. Additionally, aircraft state, navigation, and mission data are visualized through digital head-up symbology. This includes the state-of-the-art conformal symbol sets introduced in Sec. 2.3 as well as the newly developed virtual cockpit instruments (see Chapter 5). By contrast, the fully virtual cockpit virtualizes the whole HMI.

3.1.3 Virtual Cockpit Continuum in Practice

In practice, it is important to note that one is *not* required to decide for *one* type of cockpit or degree of cockpit virtuality for the *entire* flight. A fully virtual cockpit does not have to be exclusively virtual. One can also realize a "part-time" virtual cockpit where the pilots operate in a conventional flight deck during certain flight phases; and in other phases — for instance, when a wide, unobstructed external view is beneficial — they put on the HMD to work in a fully or partially virtual cockpit.

Further, the continuum should *not* be seen as a consecutive series of evolutionary stages from a conventional to a fully virtual cockpit. Instead, it is only intended to be a classification scheme for different approaches with different degrees of cockpit virtuality. Further right in the continuum means more virtual, but not necessarily that this is also the more advanced or better solution for every scenario. It may happen that current cockpits evolve step by step along this continuum to more virtual cockpits. However, in the author's opinion, it is more likely that different solutions will co-exist, each targeting specific use cases where their individual advantages come into effect.

The introduced notion of "view domains" is rather abstract at this conceptual level. In practice, their actual content may vary significantly between applications. The studies presented in Chapters 5–7 will show how implementations in different areas of the continuum can look like; the red ellipses in Fig. 3.1 illustrate their area of focus. Beyond that, many more implementations and use cases are possible within the taxonomy of the virtual cockpit continuum. At this point, it is probably good to repeat that this dissertation does not want to assess these concepts regarding certification (details later in Sec. 3.3.5).

3.2 Potentials of a Virtual Cockpit[3]

A virtual cockpit comes with many potentials and interesting capabilities. Figure 3.6 outlines the identified benefits, which are detailed in the following subsections. First, Sec. 3.2.1 explains the general advantages of immersive HMDs as opposed to PMDs and optical see-through HMDs. Thereafter, the concrete potentials with regard to the two virtual cockpit domains — external view and HMI — are elaborated (Sec. 3.2.2 and 3.2.3). Finally, Sec. 3.2.4 sketches the positive impact of a fully virtual cockpit on the overall aircraft design.

Throughout this section must be kept in mind that the potentials of a virtual cockpit depend strongly on the application scenario, i.e. type of DVE, flight maneuver, et cetera. Also, certain advantages only apply to certain degrees of cockpit virtuality (as per Fig. 3.1).

3.2.1 Advantages by the Use of Immersive HMDs

The subsequent examination concentrates on the general advantages of immersive HMDs, including video-see-through and fully occluded devices. An

[3] Parts of this section have been published by the author in [69, 73, 77].

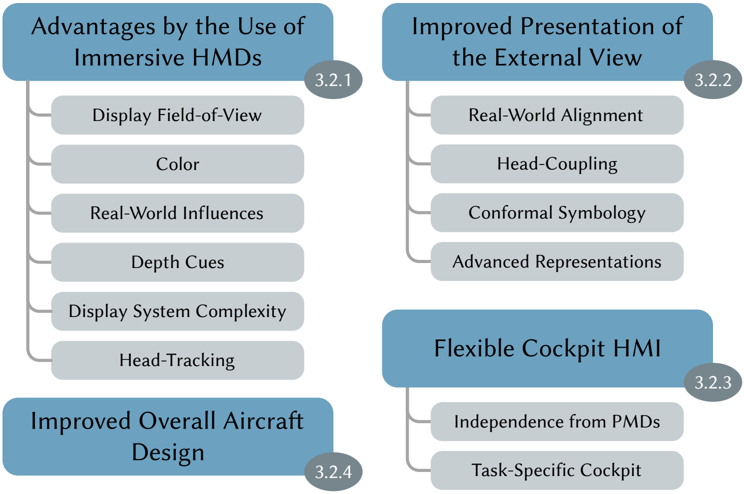


Figure 3.6 – Overview of potentials of a virtual cockpit. Each listed headword is detailed in the subsections indicated by the gray ellipses.

overview of the comparison with conventional displays is given in Fig. 3.7. The impact and relevance of certain pros and cons of a display type are application-dependent. In other words, one symbology or scenario might fit best to see-through HMDs while another flight guidance display might be better shown on a PMD. The following comparison wants to give a general overview of relevant properties, contrast the individual differences, and highlight the virtues of immersive HMDs.

3.2.1.1 Large Display Field of View

The display field of view (DFOV) defines the extent of the visual field covered by the displayed image. Typically, immersive HMDs (video- and non-see-through) offer a significantly larger DFOV than the established PMDs and optical see-through HMDs. As illustrated in Fig. 3.8, the typical DFOV of current immersive HMDs ranges around $110° \times 100°$ whereas current flight-certified see-through devices typically offer $40°$ to $50°$ [192]; new prototypes like the Elbit JedEye extend up to $80°$ horizontal [61]. A flat panel screen of

	Panel-Mounted Display	Optical See-Through HMD	Immersive HMD
Display Field of View	limited	limited	large
Color	full-color	limited, perception issues	full-color
Adverse Visual Influences from Reality	present	present	blocked by design
Depth Cues[4]	no binocular & oculomotor cues	no occlusion & shadows	most monocular & binocular cues
Display System Complexity	simple & low cost	complex optics	optics simpler than AR-HMD
Head-Tracking	not required	high accuracy required	lower accuracy requirements

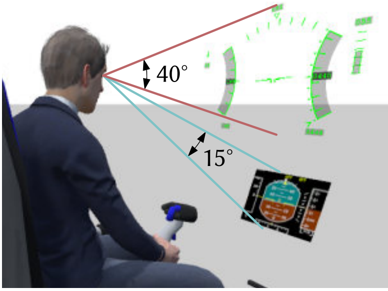
Figure 3.7 – General advantages of immersive HMDs compared to conventional PMDs and optical see-through HMDs. Immersive HMDs include both video- and non-see-through HMDs (cf. Fig. 3.3).

an Airbus A350 covers only $23° \times 15°$ if viewed from 80 cm [69]. Even though the industry works on large-area displays covering the whole instrument panel [206], the DFOV of such PMDs will still not reach immersive HMDs.

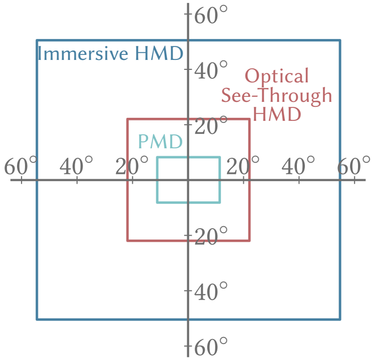
The large DFOV can have various advantages for both domains of the virtual cockpit (HMI & external view; see Fig. 3.1). First, a wide DFOV offers more freedom for the virtualization of the conventional flight deck and allows the creation of virtual instruments which are not bound to the limited size of the flat panel screens.[5] Second, a computer-generated external view can be larger and conformal flight guidance symbology and imagery can cover a wider area than on conventional vision displays. This means that immersive HMDs can generate visual cues in peripheral areas beyond the extents of established

[4] All display types have only one focus distance and thus lack the ability to create accommodation cues (details see Sec. 3.3.1.3).

[5] This idea is further expanded in Sec. 3.2.3.



(a) Three-dimensional illustration of the display field of view of typical PMDs and optical see-through HMDs.



(b) Schematic illustration of the typical[6] DFOVs of conventional panel-mounted displays and optical see-through HMDs in comparison with immersive HMDs.

Figure 3.8 – Display field of view comparison (own illustrations).

PMDs and HMDs. The benefit of such cueing was, for instance, confirmed with concepts like the Malcom horizon, which was found to significantly improve attitude control [38, 176].

In a good visual environment, this potential might be less relevant because the natural vision around the DFOV of optical see-through HMDs provides enough peripheral cues (cf. Fig. 3.3). A $40° \times 40°$ AR-overlay appears to be enough for navigation, targeting, and basic flight cueing in addition to the real out-the-window cues [192]. In DVE, however, where the display must replace missing outside visual cues through symbology or imagery, a larger horizontal FOV can be beneficial. A study by Viertler [323] seems to prove that argument: He observed that a hover maneuver at an offshore wind turbine was not safely accomplishable when an AR-HMD with small DFOV was used in heavy DVE, where the natural out-the-window view did not provide valuable cues.

Despite this advantage compared to the established display types, it is important to note that the DFOV of immersive HMDs is still smaller than the natural human visual field and that the wide DFOV often comes at the price of low angular resolution. Section 3.3.1 will discuss the effects of these limitations.

[6] Note that the FOV of certain devices is not rectangular and may vary in size.

3.2.1.2 Full-Color Symbology

Opaque HMDs can show full-color images like conventional PMDs. This is a major plus compared to optical see-through devices, which have been entirely monochrome until recently; the newest generation makes multiple colors available but color on transparent HMDs is still an issue. The color that is actually perceived by the pilot depends on the outside scene which the symbology is overlaid upon; it becomes a mixture of the natural background and the virtual overlay [123]. Further, bright daylight can desaturate the colors, which makes especially blue symbols hard to identify [205]. Even though first research in that area exists [e.g. 123, 129, 205], the selection of appropriate colors remains a complicated task because of the numerous possible real-world backgrounds. These color perception issues can be avoided altogether by using a non-transparent display.

3.2.1.3 Blocked Adverse Visual Influences from the Environment

Owing to its design, an immersive HMD blocks several adverse visual influences from the surrounding real world. This can lead to better display readability under conditions that regularly cause problems for conventional display types. VR-HMDs have no issues with external light, whereas PMDs may suffer from screen glare caused by sunrays. Even worse, optical see-through HMDs have notorious luminance and contrast issues: In bright daylight conditions, the presented symbology appears “washed out” [26]. This can be mitigated by dark visors; however, with the side-effect that the reduced light transmission also affects the real-world visibility. Often the issue is even more complex as the FOV covers dark and bright areas, which would actually require dynamic luminance adaptions based on the pilot’s gaze direction. Apart from bright environments, the readability of transparent displays highly depends on the uniformity of the real-world background. A heterogeneous, ever-changing background can strongly degrade the readability of superimposed symbology — a problem not present with an opaque HMD.

Besides better readability, immersive HMDs have the advantage that unwanted parts of the natural out-the-window view can be held off from the pilot’s eyes entirely. For instance, during a brownout landing, a pilot wearing an immersive HMD would not see the arising dust cloud. The swirled-up particles are known for creating a wrong visual impression of motion. Such misleading cues may cause disorientation resulting in inappropriate control inputs and dynamic rollover accidents, in the worst case [116]. Another example from the offshore domain are the visual cues generated by the moving waves of the ocean. These can be rather misleading if the pilot wants to hover at a fixed position over open water (see Sec. 3.4). Finally, immersive HMDs can also mitigate laser attacks from the ground — a currently very concerning safety hazard for both civil and military pilots [94].

3.2.1.4 Binocular Depth Perception

The human visual system uses various oculomotor, monocular, and binocular depth cues to understand the 3-D environment (see [44, 65, 114] for in-depth explanations). Synthetic images on a PMD and on non-transparent HMDs can reproduce many of these cues: occlusion, linear perspective, relative size & density, height in the visual field, aerial perspective, motion parallax, brightness & shadows. The advantage of HMDs is that they *additionally* trigger binocular cues by presenting one distinct image per eye, each with a laterally adjusted camera/viewpoint position (interpupillary distance). These slightly different images cause binocular disparities on the retina, which allows the perception of distances to the involved objects [114].

Finally, VR- and video-see-through HMDs outperform current optical see-through devices because of one important aspect: Virtual objects generated by the latter can neither occlude the real world nor cast shadows on it. Unfortunately, this makes a correct integration of real and virtual world impossible and may lead to confusion. Several researchers are working on solutions [109, 175] since occlusion is the most important depth cue [44].

3.2.1.5 Display System Complexity & Head-Tracking

As described in Sec. 2.1, the setup of an opaque HMD is less complex than the optical system required to relay a correct image onto the combiner of a transparent HMD. In recent years, new waveguide technology has been replacing the bulky lens systems of earlier HMDs. This closes the gap between see-through and non-transparent displays and also reduces costs. Nevertheless, simple PMDs are still the most affordable display type. Moreover, unlike

HMDs, they do not require the integration of a head-tracking system. Transparent HMDs need a highly precise and accurate tracking system to ensure correct and stable alignment between symbology and real world. Even small discrepancies are well visible and disturbing for the pilot, especially with conformal symbol sets. By contrast, non-see-through devices have slightly lower accuracy requirements because misalignment is not directly visible. Thus, small differences are hardly noticed by the pilots. Nevertheless, the tracking must still be precise enough to ensure a consistent virtual experience and safe operations. Larger misalignment may also be noticed by the vestibular system. In summary, the complexity of an HMD-based vision system is significantly higher compared to a simple PMD. However, immersive HMDs outperform at least their transparent counterparts.

3.2.2 Improved Presentation of the External View

As introduced by the virtual cockpit continuum in Sec. 3.1.1, the presentation of a computer-generated external view is one of the two major parts of a virtual cockpit. It should replace or supplement the degraded natural out-the-window view. The used display type has a high impact on how such a virtual external view can look like. Figure 3.9 shows the advantages of using an immersive HMD — as in the right half of the continuum — compared to a conventional PMD and an AR-HMD. The comparison reveals that the novel display method appears to overcome the individual limitations of the established displays by combining their respective advantages. One can realize a head-coupled, real-world-conformal view with scene-linked symbology like on an AR-HMD but with the full control and freedom that an opaque screen offers for the information presentation (similar to PMDs). The following subsections discuss these aspects in detail.

3.2.2.1 Real-World-Aligned & Head-Coupled View

The paramount feature of head-tracked HMDs is the possibility to generate a virtual view that is aligned with the real world. Such a conformally superimposed external view can be realized on both transparent and opaque HMDs; it has several advantages compared to a vision display rendered on a PMD.

	Computer-Generated External View on		
	Panel-Mounted Display	Optical See-Through HMD	Immersive HMD
Real-World-Aligned Virtual View	impractical, usually scaled-down	conformal, 1:1 scale	conformal, 1:1 scale
View Direction Control	fixed or manually adapted	head-coupled	head-coupled
Conformal & Scene-Linked Symbology	only to non-conformal PMD view	to real out-the-window view	to virtual out-the-window view
Advanced External View Representation	full control, many options	overlay only	full control, many options

Figure 3.9 – Advantages of a computer-generated external view presentation on an immersive HMD compared to a conventional PMD and an optical see-through HMD. Immersive HMD includes both video- and non-see-through HMDs (cf. Fig. 3.3).

As discussed above, conventional PMDs have a rather small DFOV. This means that a one-to-one scaling of the displayed viewing volume — called geometric field of view (GFOV) [16, 287] — is impractical because it would restrict the computer-generated view to a small area. Thus, a larger GFOV is usually chosen [e.g. 207, 310]. However, this results in a scaled-down and often distorted picture of the displayed scene [278, 310]. Such a minified view complicates the recognition of details and has been shown to promote the underestimation of relative distances [24]. Also, worse flight path tracking and diminished control performance have been observed because smaller display scales make small deviations less visible [216].

A conformal HMD-based view does not have these minification issues and additionally allows the pilots to naturally control the viewing direction; they just have to turn their head towards the region of interest as they would naturally look around in the real world. This is especially relevant for helicopter crews because their specific mission characteristics require the monitoring of the surroundings in all directions. Adapting the viewing direction of a

PMD-based vision display would require manual user inputs — which is of course not as intuitive as natural head rotation. Despite these advantages, real-world alignment also means that relevant information may be spread across the whole FOV and in the worst case even beyond. Chapter 7 addresses this problem with the development of an exocentric view.

The characteristics of an immersive external view also reduce the mental integration effort for the mapping of reality and virtuality. With a conformally superimposed virtual world, the head and eye pose tells the pilot where the currently seen object is located. Turning the head by 90° simply means seeing objects on the side. The virtual view presentation coincides with how humans perceive the real world in their daily life. By contrast, a synthetic view on a PMD involves a scaled-down 2-D projection of the 3-D world; the viewing direction does not intuitively reveal where a displayed object is in reality. An object located at 45° might appear only a few degrees off the display center line. The correct interpretation requires additional information about the GFOV or must be derived by comparing landmarks of virtual and real out-the-window view. This can lead to better spatial orientation and less mental workload with a VR-HMD compared to a 2-D projected wide-angle view [1].

3.2.2.2 Conformal & Scene-Linked Flight Guidance Overlays

State-of-the-art research presents many valuable ways of integrating additional flight guidance information into the external view. Superimposed symbology that is displayed in a conformal or scene-linked way has been shown to support pilots in aircraft control and navigation while reducing workload and improving situation awareness (see Sec. 2.3). The researched symbologies include solutions for low-altitude flight, hover, and landing. The most famous examples are tunnel-in-the-sky for flight path guidance and virtual touchdown zones for DVE landings. Generally, such overlays can be implemented on PMDs and HMDs. However, the limitation of the former is that the symbology will only be conformal to the synthetic PMD view which itself is not aligned with the real world, as discussed above. All types of virtual cockpits can make use of the advantages of conformal and scene-linked flight guidance concepts. The well-proven approaches from see-through display design can be transferred to immersive HMDs in a virtual cockpit. Thereby, they will additionally profit from the general advantages of opaque displays described in Sec. 3.2.1 (e.g. larger DFOV, full-color, no real-world disturbances). The virtual cockpit implementations presented in Chapters 6 and 7 will demonstrate the beneficial application of conformal symbologies in a virtual cockpit.

3.2.2.3 Advanced External View Representation

Another advantage of using an immersive HMD are the many options for an advanced representation of the external view. This fits perfectly with the author's goal of creating an ecological display, in the sense that the computer-generated external view should provide the cues that pilots naturally use to move through a good visual environment (cf. [347]).

All considered displays have in common that they want to provide the visual cues that are missing in DVE. However, they follow two distinct approaches: Optical see-through HMDs superimpose symbology onto the degraded natural out-the-window view; whereas PMDs and immersive HMDs create a computer-generated world that replaces the direct outside vision with fused input from sensors and databases — which outperforms the natural vision.

The visualization options for see-through displays are limited because the terrain and obstacle representations must be designed as an overlay that blends with the remaining parts of the natural out-the-window view. To avoid clutter and masking of the reality, only plain symbol sets with few lines can be drawn (see Sec. 2.2.6). Further, display limitations like restricted DFOV as well as limited color and depth cueing opportunities (see Sec. 3.2.1) make it impossible to fully replace the missing out-the-window cues in DVE with an AR-HMD. Especially microtextures,[7] which are very important for hover and low-speed maneuvering [130], can hardly be supplied on see-through HMDs without cluttering the view and occluding too much of the real world [323]. For instance, Viertler [323] showed that his macrotexture-based see-through symbology was not enough for a DVE hover maneuver at an offshore wind turbine if the remaining natural outside view did not provide at least an amount of microtextures.

[7] The cue-providing elements of a scene can be classified into macrotextures (large objects) and microtextures (fine-grained details). For details refer to [130] or Sec. 6.1.2.

By contrast, with an immersive HMD, one cannot just add a virtual overlay onto the DVE but generate advanced, digital views. One can create a completely virtual and DVE-free world that perfectly fits the pilot's requirements. The visualization options are similar to those of PMD-based synthetic vision displays; however, combined with the above-mentioned advantages of a real-world-aligned, wide-angle representation.

While re-creating the outside visual cues on the display, one should be aware of what Smallman and John [281] call "naive realism": Photo-realism is often preferred by the user, but does not necessarily result in better performance than abstract visualization. For a virtual cockpit, this means that the virtual external view should correspond to the pilot's mental model and reflect important characteristics without aiming for photo-realism, even though an opaque display would allow that. The development of a computer-generated view of the ocean surface for offshore flying in Chapter 6 shows the application of this maxim; it includes abstract visualizations which are reduced to the relevant information only.

3.2.2.4 A Whole New World of Possibilities

In summary, the described aspects open up a whole new world of possibilities for the creation of a virtual external view. One can, for instance, let the pilots "see through" the structure of their aircraft. Instead of seeing the cockpit floor when looking down, they would see a digital view of what happens below. Further, as the external view on an immersive HMD is uncoupled from the natural egocentric view, one can even realize virtual views with an exocentric viewpoint. This means that the pilots are immersed in a 1:1-scaled virtual world but not as seen from their natural cockpit viewpoint; instead, they virtually step out of the helicopter and perceive the situation from another position which gives a better overview of the surroundings. The potentials of these new possibilities are thoroughly examined in study IV (Chap. 7).

3.2.3 Flexible Cockpit HMI Layout

A virtual cockpit has not only advantages for the external view visualization but also introduces many positive aspects for the realization of the HMI — the second domain in the author's notion of "cockpit" (see Fig. 3.1). To realize a virtual flight deck, one could just replicate the conventional instrumentation in the virtual world like it is done in VR flight simulators (see Sec. 2.1.5.1). This may work, but — as this work will show — VR offers much more.

Years ago, when multi-function display screens were introduced in cockpits, the information presentation gained more flexibility compared to the preceding analog gauges. This change removed the constraint of analog instruments being fixed to displaying only their pre-defined information. Modern multi-function displays allow the pilots to adapt the displayed information according to their needs, which is especially important as the system complexity and number of parameters increase steadily. Nevertheless, even though the display content can be adapted easily, the information presentation is still restricted to the flat-panel screen: The position, the size, and the number of the available PMDs cannot be changed.

A virtual flight deck removes this restriction: The optics of an HMD can create an HMI that is very flexible; one can easily change the virtual displays and adapt the symbology to the current flight phase or task. As presented in Sec. 2.1.5.3, many engineers and human factors specialists have been imagining such future cockpits with virtual instruments created by an HMD.

In a partially virtual cockpit, one can create additional virtual screens to supplement the physical flight deck instrumentation as described by Comerford and Johnson [37] and implemented in this dissertation with the so-called "virtual cockpit instruments" in Chapter 5. The reader is referred to this chapter for implementation details and a pilot-in-the-loop evaluation of advantages and limitations.

A fully virtual cockpit offers even more freedom for the implementation of the HMI. Much information that is conventionally presented on PMDs can be visually integrated into the external view. This is especially the first choice if the information is related to the real-world environment. It hardly makes sense to create a virtual version of a head-down synthetic vision display if one can immerse the pilot in a real-world-aligned, stereo version of a computer-generated external view as described above. Similarly, a wide conformal horizon makes small deviations better visible than a small artificial horizon — which itself still has benefits for unusual attitudes. Other information can or should not be integrated into the 3-D scene: Checklists, system displays, and similar data can be shown on virtual screens positioned around the pilot. Figure 3.10 illustrates these ideas.

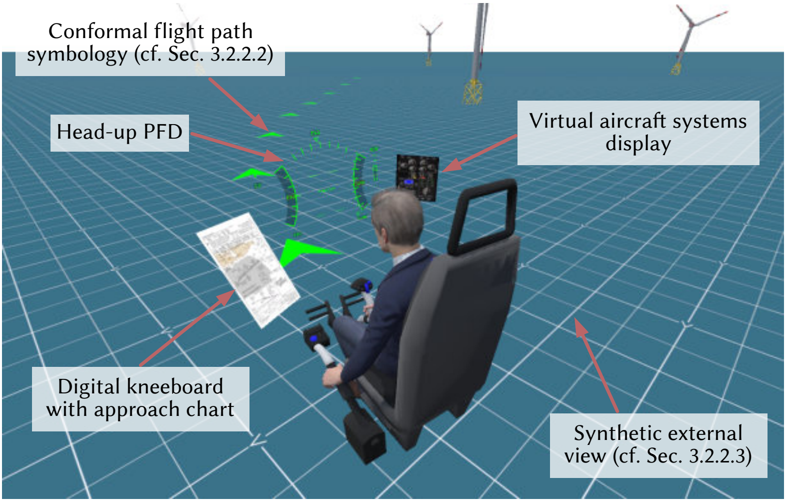


Figure 3.10 – Illustration of a fully virtual cockpit with flexible HMI. The HMD creates an environment where the pilot can "look through" the aircraft hull, perceive visual cues from a synthetic external view, and interact with task-adapted, virtual displays. All these aspects are further evaluated in Chapters 5–7 (own illustration).

The size and position of these virtual screens can be individually adapted to the specific display contents and to the requirements of the current task. Also, the number of virtual screens can be changed dynamically by the pilot. This means that one can generate additional display areas which can be positioned and sized according to the needs of the pilot. During the approach, a pilot can — for instance — open a new virtual screen displaying an approach chart. This "digital kneeboard" can be positioned above the knees like its analog counterpart but also anywhere else around the pilot. As soon as the information is not needed anymore, a virtual screen can be completely hidden to de-clutter the pilot's view.

In summary, an immersive HMD makes it possible to create the "perfect" cockpit for each flight phase; the whole virtual HMI can instantaneously be adapted to the current task. In theory, this flexibility is a major benefit. However, as Sec. 3.3.2 shows, extensive research and development regarding the interaction with such a virtual HMI will be required to actually realize such highly or fully virtual cockpits.

3.2.4 Improved Overall Aircraft Design with a Fully Virtual Cockpit

A standalone, fully virtual cockpit as described in Fig. 3.5 requires neither cockpit windows nor the traditional flight deck instrumentation. This results in several benefits for the design and construction of the whole aircraft. The following examples show that the exact advantages can be very different depending on the type of aircraft considered, i.e. civil or military, rotary or fixed wing.

The replacement of conventional cockpit hardware through a virtual HMI produced by a single HMD has the potential to reduce aircraft weight, space requirements, and system costs. Moreover, an HMD emits significantly less light than traditional cockpit screens. This means that the visibility to others, which is a major concern for military aircraft, could be considerably reduced with a virtual cockpit — even in an early stage with normal cockpit windows.

The removal of cockpit windows saves weight, reduces costs, and allows for the design of an aerodynamically optimized aircraft fuselage. Regarding military aircraft, one could substantially improve the armor plating if fewer glazed surfaces are needed. Beyond helicopter DVE operations, aerodynamic optimization is especially relevant for supersonic configurations. Being able to realize a lancet-shaped nose without the need for a droop mechanism like on the Concorde, also created the motivation for previous research on XVS [156, 277] (details see Sec. 2.2.2.1). Moreover, a windowless cockpit can be localized outside of the nose section. Moving an airliner cockpit closer to the aircraft center, control surfaces, and engines could potentially reduce cable lengths, which saves additional weight. Also, the free space in the forward section may be used to enlarge the passenger cabin.

Of course, the realization of a windowless cockpit is not intrinsically linked to an HMD-based virtual cockpit. The external view could also be provided by flat-panel displays as Kramer et al. [156] showed. However, it has to be considered if other reasons like the head-coupled, conformal representation of the environment argue for the usage of an HMD. This can also be an argument for a virtual cockpit as “control station” for remotely piloted aircraft systems.

3.3 Challenges for a Virtual Cockpit[8]

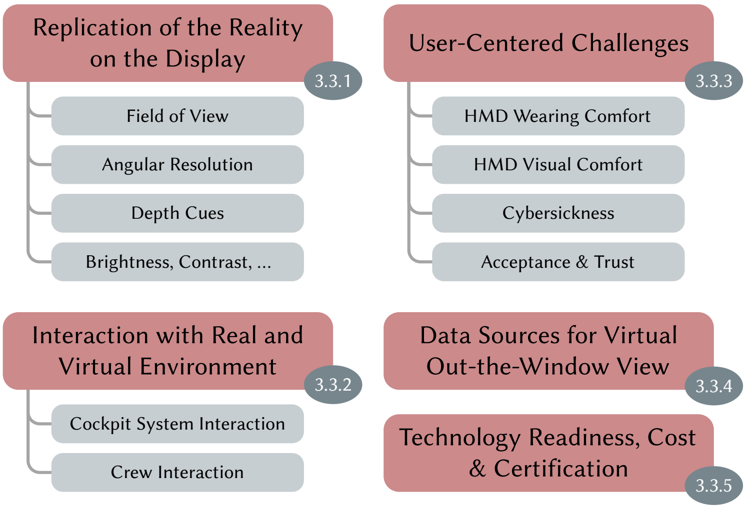


Figure 3.11 – Overview of challenges for the realization of a virtual cockpit. Each listed headword is detailed in the subsections indicated by the gray ellipses.

Despite all advantages, a virtual cockpit also entails a number of limitations and challenges to be met before the approach can be realized. This includes the restricted capabilities of current HMDs but also conceptual issues that arise if the real environment is replaced by a virtual HMI and a synthetic external view. Figure 3.11 gives an overview of the main challenges identified by the author. The following sections detail and discuss these issues. Moreover, ideas and current research that could solve these problems are presented.

3.3.1 Replication of the Reality on the Display

Current HMDs are not capable of replicating what the pilots usually see when looking out of the cockpit windows. The limitations include restricted FOV, lower-than-human-eye resolution, unnatural depth cues, and more. The

[8] Parts of this section have been published by the author in [69, 77].

following sections provide a detailed description of these restrictions, followed by a discussion on what these mean from a practical point of view.

3.3.1.1 Restricted Display Field of View

HMDs offer a head-coupled field of regard and a wider display field of view (DFOV) than PMDs (see Sec. 3.2.1). However, current devices can still not provide a view that covers the whole human visual field. As illustrated in Fig. 3.12, the typical DFOV of current HMDs is much smaller than the human visual field, which varies between individuals but typically extends to around $210° \times 130°$ [26, 288, 322]. This means that HMDs cover the most important central part of the human vision, the area where eye movements and focal vision happen. However, the displays are more (non-immersive, see-through HMDs) or less (immersive HMDs) limited in the peripheral areas. The ambient vision is especially important for egomotion perception, presence, and spatial awareness [43, 222, 347].

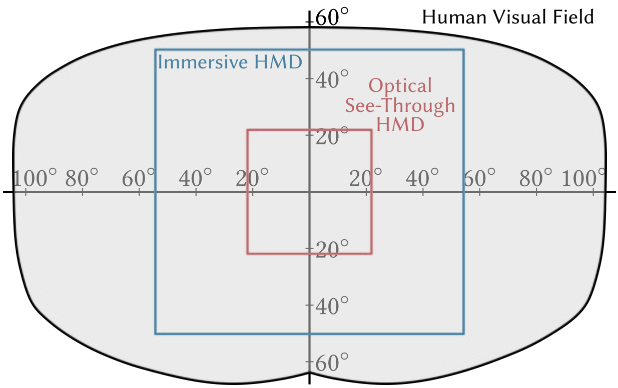


Figure 3.12 – Schematic illustration of the typical[9] FOVs of optical see-through and immersive head- or helmet-mounted displays in comparison with the human visual field (own illustration).

At this point, it is very important to remember that the type of HMD — non-immersive or immersive — has very different effects on what limited DFOV means for the pilot's overall view. As already shown before in Fig. 3.3, a

[9] Note that the FOV of certain devices is not rectangular and may vary in size.

non-immersive HMD allows the pilot to see the reality throughout the entire visual field; the DFOV is the area where symbology is overlaid. In contrast, an immersive HMD blocks the pilot's whole vision outside of the DFOV; typically, this means that the outer 50° on both sides of the visual field are masked and cannot provide any visual cues. In other words, the DFOV of non-immersive HMDs like the flight-certified AR-HMDs limits the area where *additional* visual cues can be shown, whereas the DFOV of immersive HMDs defines where visual cues will be available at all.

Synthetic vision displays on PMDs try to compensate for the limited DFOV by increasing the geometric field of view (GFOV). This means that the synthetic view has an aperture angle wider than the visual angle covered by the PMD in the pilot's natural view. With this approach, scaled-down egocentric views showing up to 360° around the pilot can be realized [206]. For HMDs, such an approach appears to be impractical. HMDs require a one-to-one mapping of GFOV and DFOV [287]. Any other relation would lead to a non-conformal connection of postural and visual information: It would be very confusing if the head posture indicates, for instance, a head turn of 45° while the display shows the scene as if the pilot was looking 90° to the side. Chapter 7 will show that the presentation of an exocentric perspective view can increase the space visible to the pilot without the need for a larger DFOV. Nevertheless, even though such methods can increase the visible amount of the surroundings, actual peripheral cues can only be provided with a large DFOV. Thus, the manufacturers are challenged to advance wide-FOV prototypes [e.g. 242, 250, 286] and make them comfortable for long-time usage.

Is Replication of the Real World Really Needed? It is certainly a legitimate goal to aim for exact replication of the real world. Nevertheless, from a practical perspective, this may often not be required to fulfill certain tasks. A FOV that is too small degrades pilot performance, but what is "too small" and is the whole human visual field actually required? The right size depends on the application and task. Several studies evaluate the impact of a restricted FOV on the performance of typical helicopter maneuvers. Hoh [130] found that low-speed flight and hovering is in principle possible with a very small FOV (38° × 23° in his case), but only if the view offers enough microtextures. Nevertheless, the performance was found to improve for various ADS-33 mission task elements as the FOV was widened from 20° to 60° or 80° [127]. An even wider FOV did not increase performance but is recommended to reduce workload and fatigue (because of fewer head movements) [139]. For cockpit interaction, Chevaldonné et al. [32] suggest a horizontal FOV above 75°, as close as possible to 130°. Aside from helicopter operations, Arthur [6] discovered that locomotion and search task performance for pedestrians increases even from 112° to 176° horizontal FOV. In summary, one can conclude that — even though the FOVs of current immersive HMDs do not reach the extent of the human visual field — they meet many requirements defined by previous research. Further, it must be kept in mind that the FOV may be smaller than the human visual field, but it is often still larger than the extent of the real world visible through the cockpit windows (cf. Sec. 2.2.1). Nevertheless, the author recommends to further investigate the FOV requirements for the specific case of a fully virtual cockpit.

3.3.1.2 Below Human-Eye Resolution

High spatial resolution is required for the pilot to see small and distant objects in the far domain as well as to recognize details and read alphanumeric information of the symbology in the near domain. Further, the ability to render small details and fine-grained textures (i.e. microtextures) is important for depth and egomotion perception during hover and low-speed maneuvering [130]. As detailed in Sec. 2.2.1, an angular resolution of one arc minute (1/60 deg) is often stated as the minimum requirement to reflect "normal" visual acuity. This would require a pixel density of at least 60 pixels per degree (ppd). Higher densities are needed to reproduce hyperacuity. Better resolution also prevents jagged edges and lines, which reduces the need for anti-aliasing.

Conventional HMDs have an image source with a certain number of pixels, which are magnified by the optical system to cover a certain area of the user's view. The angular pixel density can be roughly[10] computed by dividing the image resolution by the FOV. This formula describes an HMD design trade-off, which is known as the FOV/resolution invariant [188, 192]: increasing the FOV results in larger pixels and lower angular resolution. In other words, the wider the FOV, the higher the display resolution required to reach 60 ppd.

Traditional AR- and VR-HMD designs can currently not provide this desired resolution together with an also desired wide FOV. Consumer VR goggles

[10] Usually, the optics do not distribute the pixels entirely uniformly over the FOV; the angular resolution decreases somewhat on the sides [163].

usually choose FOV over angular resolution to create a feeling of immersion and presence. For instance, the Oculus Rift CV1 has approximately 110° diagonal FOV and 1080×1200 pixels per image source, which results in an angular pixel density of around 13.8 ppd [163]. By contrast, AR glasses like the Microsoft HoloLens 2 trade a high angular resolution — above 43.6 ppd [198] — for a smaller FOV of around 52° diagonal [115]. The flight-certified Elbit JedEye HMD offers a compromise: approximately 27 ppd with a total FOV of $80° \times 40°$ and 2200×1200 pixels [61]. For comparison, the cockpit instrument screens in an Airbus A350 cover around $23° \times 15°$ of the pilot's view and reach about 61 ppd [69].

With the conventional design of the above-mentioned HMDs, one would require $12\,000 \times 6000$ pixels to reach 60 ppd over a wide FOV of $200° \times 100°$. However, such a high pixel density over the whole display is actually not needed. Only the inner area of the human retina — the fovea — has this high visual acuity. For the peripheral areas, a lower pixel density is sufficient. Novel HMD designs take advantage of this knowledge by following two strategies [161]: 1) digital foveation (often called foveated rendering), and 2) optical foveation. The former makes the graphics engine produce a high-resolution image that is digitally embedded into a peripheral low-resolution image. In its simplest implementation, the inner focus area is static; which makes use of the fact that most saccadic eye movements happen within ±15° [192]. If a target is outside this area, the user commonly[11] moves the head to avoid extensive eye rotations. However, a better visual experience is achieved by tracking the user's eye movements and moving the high-resolution area accordingly [119, 233]. Figure 3.13 sketches both the static and the dynamic variant.

Foveated rendering certainly reduces the rendering effort, but a conventional design with one uniform image source still requires a high pixel count. Thus, the second technique — optical foveation — applies two distinct image sources: a low- and a high-resolution display [161]. Similar to the idea of foveated rendering, the focus display can be fixed in the center of the view or dynamically steered based on gaze direction. As illustrated by Kress [161], the last variant obviously has the lowest native display pixel count and rendering requirements. Optical foveation is implemented by the new Varjo XR-HMDs,[12]

[11] IFR pilots train to reduce these head movements in favor of long saccades.
[12] This next generation of HMDs was not launched until the last study of this thesis was finished.

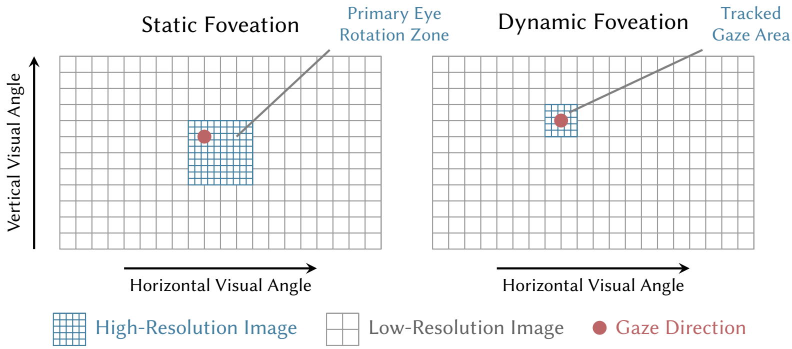


Figure 3.13 – Schematic illustration of HMD designs that take advantage of the specific human eye characteristics by combining a high- and a low-resolution image. Static foveation has a fixed focus area covering the zone where most eye rotations happen. Dynamic foveation features a high-resolution image that follows the wearer's eye gaze. Optical and digital foveation implement both general concepts in different ways (own figure, based on [161]).

which use a mirror system to combine a 70 ppd focus area display ($27° \times 27°$) with a 30 ppd image source for the peripheral areas [161, 321].

Is Replication of the Real World Really Needed? Two aspects are important for the interpretation of current VR goggle resolutions. First, even though they do not reach human-eye capabilities in optimal viewing conditions, they may still perform better than the naked eye in many DVE situations, which is the targeted scenario of a virtual cockpit. Fenley et al. [96] provide an overview of DVE operational levels and state that ADS-33 usable cue environment (UCE) level 1 relates to a Snellen acuity[13] $< 20/50$, UCE 2: $< 20/80$, and UCE 3: $> 20/80$. The second important aspect is that a virtual cockpit is not intended to show raw sensor imagery but a computer-generated picture of the environment. The pilots will see a virtual scene with good visual conditions and cueing of sensor-detected obstacles and targets. In such a setup, the resolution requirements for the display hardware are certainly lower than in setups where the pilots have to detect low-contrast objects on the raw imagery by themselves. For example, the camera-based sense and avoid system by

Thus, the following simulator studies used the conventional lower resolution devices.

13 A Snellen acuity of 20/20 is considered normal visual acuity. Refer to Sec. 2.2.1 for details.

Minwalla et al. [203] transfers the traffic detection task from the pilot (cf. NASA's XVS, Sec. 2.2.2.1) to the sensor system. It thereby exceeds the typical visual acquisition ranges. If such a system can highlight intruder positions, a high-definition image source may not be required.

3.3.1.3 Depth Cueing Limitations

Despite its advantages for the presentation of 3-D environments (Sec. 3.2.2), current HMD technology can still not fully replicate all depth cues available with natural vision [51]. A well-known problem is the limitation to a single focus distance and the accompanying vergence-accommodation conflict.

Looking at an object in the real world involves two oculomotor processes [114]: The eyes turn inward to fixate the object (vergence). Simultaneously, the lenses bring the object into focus and create a clear image on the retina (accommodation); closer and farther objects appear blurry. In Fig. 3.14, the two mechanisms are depicted in red and blue respectively. Naturally, both processes are coupled and the changes of the respective eye muscles are interpreted by the brain to estimate the object distance [347].

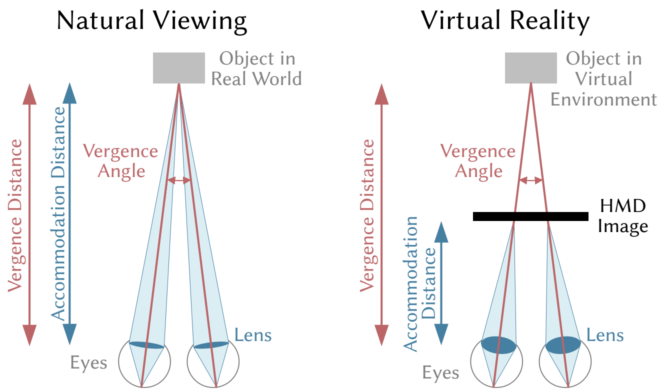


Figure 3.14 – Vergence-accommodation conflict (inspired by [31, 230]).

Current VR-HMDs, however, create an unnatural viewing condition because the whole scene is presented at the same optical distance. This removes a relevant depth cue: the retinal blur of objects not in focus [134]. Even worse, it forces a disconnection of the naturally coupled vergence and accommodation mechanisms, as illustrated in Fig. 3.14: The stereoscopic scene presentation triggers the same vergence angle as the real object but the eyes must accommodate to the short optical distance of the display screen [31, 230]. These mismatches can lead to visual discomfort, distance perception problems, and other issues [204, 230]. Current research uses eye-tracking and dynamically adjustable optics to adapt the focus distance depending on where the user looks at [134, 230].

Is Replication of the Real World Really Needed? For the discussion about limited depth cues, one should note that not all depth cues are equally important and that their effectiveness varies with the distance between observer and object [114, 347]. While occlusion appears to be the most effective cue for all viewing distances, the conflicting vergence and accommodation are only important in the near space below approximately 10 m [347]. This means that they are relevant for the virtual cockpit environment and for the hand–eye coordination to interact with close objects; but they are hardly necessary for most of the outside vision. Current vision systems on PMDs, HUDs, and AR-HMDs cannot provide these cues either. Even worse, the currently flight-certified transparent HMDs and HUDs cannot even correctly reproduce the important occlusion cues between real and virtual objects.

3.3.1.4 Further Display Limitations

Limitations of FOV, resolution, and depth cueing are probably the most relevant concerns regarding the replication of the real world on current HMDs, but many other aspects play a role. These include brightness, contrast, black level, temporal resolution, color fidelity, binocular fusion, and display update lag. More details can be found in [46, 234] as well as in the literature on vision systems presented in Sec. 2.2.

3.3.1.5 Conclusions

In summary, current HMDs cannot perfectly replicate the reality. However, the previous findings also show that for many scenarios an exact replication may actually not be required and the available capabilities can be sufficient. Moreover, the newest research efforts and next-generation prototypes give rise to optimism that the discussed restrictions are getting smaller and fewer. Nevertheless, it is very important to be aware of the limitations in comparison with the natural view. Only this knowledge makes it possible to develop an appropriate virtual cockpit. The studies presented in Chapters 5–7 will show that the limited display capabilities of the Oculus Rift CV 1 seem to be basically sufficient for the applications developed within this work.

3.3.2 Interaction with Real and Virtual Environment

3.3.2.1 Interaction with Cockpit Systems/Instruments[14]

A human-machine interface like the virtual cockpit has two equally important directions of information flow: *Displays* present the output from the system to the user. Vice versa, *input devices* transfer the user's intentions to the machine. Traditional cockpits comprise various types of input devices: flight controls (cyclic, collective, pedals), push buttons, dials, toggle switches, 4-way-switches, and different cursor-control-devices (thumb-/fingerstick, trackball/-pad) [311]. The development of practical and reliable input devices for a virtual cockpit will be a major challenge because many conventional methods do not work anymore if the physical instrument panel is replaced by virtual instruments on an HMD (cf. Sec. 3.2.3).

In the author's opinion, there are two approaches to enable human-machine interaction in a virtual cockpit:

1. try to replicate the common hand/finger interaction paradigms for the virtual space, or
2. integrate other input modalities specifically targeting the peculiarities of a virtual cockpit.

The first approach is — for obvious reasons — adopted by the VR-based flight simulators presented in Sec. 2.1.5.1. The four common techniques are compared in Tab. 3.1 and illustrated in Figs. 3.15 and 3.16. As depicted in Fig. 3.15a, a fully virtual setup has no real input hardware; it only shows virtual user interfaces via the HMD. A button press is detected via a finger-tracking system [8]. This leads to a very flexible, easily re-configurable user interface. However, the main problem of virtual-only input devices is the absence of a

[14] Parts of this section have been published by the author in [75].

counter-force and the missing natural haptic feedback. Pressing a physically not existing button is not intuitive and makes a trivial task unnecessarily complicated. Thus, Schiefele et al. [265] implemented a simple feedback mechanism by mounting flat plastic panels at the button locations such that the pilots felt when they reached the button. Of course, this takes away the ability to easily change the virtual user interface, e.g. for another task (cf. Sec. 3.2.3). Further, the haptic experience is limited to pressing onto a flat surface.

Table 3.1 – Comparison of different approaches to replicate common hand/finger interaction paradigms for the virtual space. See Figs. 3.15 and 3.16 for illustrations of the various setups.

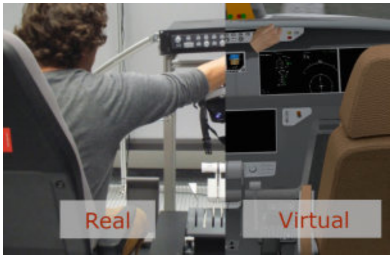
	Input Detection	Perceived Realism	Flexibility of the User Interface
Fully Virtual	finger-tracking	low[a]	high
Simple Feedback	finger-tracking	rather low[b]	low[c]
Haptic Gloves	finger-tracking	rather high[d]	high
Mixed Setup	real input device	high	low[e]

[a] no haptic feedback provided.
[b] haptic feedback from plates is rather limited and unspecific.
[c] feedback plates are at fixed locations.
[d] technology under development, first devices demonstrate high potential.
[e] real input hardware is at fixed locations.

A solution to this can be haptic gloves (Fig. 3.16). They apply various techniques, from simple vibrations [180] to light-weight exoskeletons [274] and microfluids [122], to generate a natural feeling of touching a virtual object. This approach promises to provide a high degree of realism while still allowing to instantaneously change the virtual cockpit interface. Such concepts have been researched for decades and the current device generation seems to come closer to meeting the high expectations of that technology.

The most realistic user interaction is generated with a mixed reality setup as implemented by Oberhauser and Dreyer [224] in Fig. 3.15b: A real input device (stick, touch display, etc.) receives the pilot's inputs and provides haptic feedback, while the HMD shows a visual representation of the input hardware. Such an interaction concept is in line with the notion of a partially virtual cockpit as presented in Fig. 3.1. Physical elements can be made visible

(a) Fully virtual setup — buttons are virtual-only and finger-tracking detects "button presses".



(b) Mixed setup — virtual representations of input devices have real hardware counterparts receiving user inputs and providing haptic feedback.

Figure 3.15 – Different hand interaction setups in a virtual cockpit [227] (Reproduced with permission from Springer Nature).

by using optical or video see-through HMDs or by placing a digital model of the object in a fully virtual environment. Obviously, the higher interaction fidelity is paid for with lower flexibility. Video-see-through HMDs make it possible to show a video stream of the user's hands and real input hardware (if available) integrated into the otherwise virtual world. This may appear more realistic than an entirely computer-generated world as depicted in Fig. 3.15.

The author and the available literature [224, 265, 354] agree that a mixed setup is the preferred way for the flight control elements because the required realism and reliability can currently not be achieved without the actual hardware devices; and flexibility is not needed for these elements of the cockpit. Having such a mixed flight control setup, one can easily establish "hands on throttle and stick (HOTAS)" concepts known from fighter jets [141, 311]. This means that pilots can keep both hands on the flight controls while still being able to execute all important cockpit functions via the buttons and cursor control devices integrated into the stick and thrust lever. Further, such a setup is the most robust input method in the presence of turbulence or accelerating forces in general, because the pilot can "hold on" to the input device. The author applies this approach in all four experiments presented in this thesis.

However, one should not only focus on realizing hand/finger interactions in the virtual space. Instead, one should also consider other input modalities which may better fit the peculiarities of a virtual environment. This development of new user input concepts is not only a challenge; it presents an

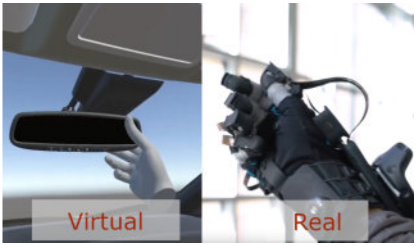


Figure 3.16 – Haptic gloves — user interfaces are virtual-only, finger-tracking detects interactions, and haptic technology within the gloves provides force feedback [120, 121] (© 2019 HaptX, Inc.).

opportunity at the same time because many common interaction techniques do not necessarily best match with the pilots' basic cognitive and psychomotor capabilities [311]. Great potential for reducing the cognitive load is seen by integrating bio-centric modalities which conform better to the natural perceptual and cognitive skills:

- voice commands,
- hand gestures,
- head-aiming,
- gaze-based interaction (eye-tracking), and
- brain-actuated control. [107, 110, 132, 218, 311].

Head-aiming has been used successfully on several generations of military aircraft to designate off-boresight targets significantly faster [275]. Also, voice input is already established in fighter aircraft ("voice, throttle, and stick" concept, see [141]). Several researchers predict that eye-tracking will potentially improve future human–computer interaction [110, 311].

In conclusion, the development of intuitive and reliable interaction mechanisms will certainly be a critical building block for the introduction of a virtual cockpit. Luckily — since suitable input modalities are a key success factor for all kinds of AR/VR applications — many novel approaches are under development. However, further work will be needed to advance them to a state as mature as required for an application in an aircraft cockpit. The selection of appropriate input devices will depend on the use case and on the degree of cockpit virtuality (as per Fig. 3.1). For a partially virtual cockpit, a mixed-reality approach with synchronized real and virtual elements via video-see-through HMDs appears to be a suitable approach. Auspicious new methods like voice control, head-/gaze-based interfaces, and haptic gloves seem to be promising for fully virtual setups in the long term.

3.3.2.2 Crew Interaction

Pilots do not only interact with the machine but also with their co-pilots or crew members. Using an HMD as primary display involves at least two issues regarding crew interaction. First, with both see-through AR- and occluded VR-HMDs, pilots cannot perform instrument cross-checks as they cannot see each other's displays. Second, with a VR-HMD, the pilots cannot directly see each other. This will probably be more a trust and acceptance problem than an actual function or performance issue. A possible remedy could be the application of video-see-through HMDs, which can selectively integrate a video of the crew member into the virtual cockpit environment. In the future, the introduction of single-pilot operations may remove these requirements entirely.

3.3.3 User-Centered Challenges

A virtual cockpit requires the pilot to wear an HMD for a long time. This makes ergonomics and comfort a key requirement for the acceptance of this approach. To ensure wearability, an HMD must be light-weight, must have a well-balanced center of mass, and should be adjustable to the individual head form and eye geometry [189]. Further, the optical design has to ensure viewing comfort and avoid visual fatigue, eye strain, and other adverse effects.

Current flight-certified HMDs are usually worn by military pilots who are already used to wearing helmets and trained to work under demanding circumstances. To reach acceptance in civil aviation, the benchmark regarding comfort will certainly be higher, probably similar to the ergonomics requirements of consumer products. Further, VR-HMDs pose different comfort challenges as they completely block the natural view and occlude major parts of the peripheral vision. The HMD manufacturers made great progress over the past few years. However, the author's experience with many participants in various simulator studies (see Chapters 5–7) shows that current goggles can only be worn for a few hours with several breaks in between.

Cybersickness is another important issue to be addressed when a virtual cockpit is developed. For 67 % of adult users, VR-HMD experiences regularly cause mild to severe symptoms like sweating, nausea, dizziness, headaches, et cetera [304]. Often, display latency or a mismatch between the visual and the vestibular senses are considered as sources for these effects. Rebenitsch and Owen [253] give a thorough overview of the current state of knowledge. It shows that cybersickness issues are manifold, varying between individuals, and often still not fully understood. Current-generation HMDs appear to reduce adverse effects [152]. Moreover, careful selection of the presented content is required to minimize sickness symptoms [262]. Finally, various techniques like dynamic FOV restriction [169, 304] or predictive compensation of apparent latency [29] have been shown to reduce cybersickness and may be applied in future HMD generations.

All mentioned factors will have a major impact on the overall acceptance of such a system. Additionally, wearing an opaque HMD during the flight will require great trust in the system.

3.3.4 Data Sources for the Virtual Out-the-Window View

The creation of a virtual external view requires data sources that provide all relevant information. As described in Sec. 1.1, the author envisioned his approach building on the same data acquisition that is used for conventional display solutions. This means that a virtual cockpit faces challenges that are fairly similar to the existing vision systems. Section 2.2 covers these extensively. In summary, the data must be reliable, up-to-date, high-resolution, and accurate. Further, the latency, i. e. the lag between the real and the virtual world, must be in an acceptable range, preferably within 50–100 ms [170]. For further reading, EUROCAE's ED-255 [81] provides a thorough overview of requirements for helicopter CVS.

The exact requirements for an individual system can be very different; they depend on the intended system function, the targeted types of DVE, and the degree of cockpit virtuality. For an AR-based solution targeting a very specific scenario, the data source requirements are certainly lower than for a fully virtual cockpit. For instance, the virtual instrument approach developed in Chapter 5 virtualizes only parts of the cockpit while preserving the natural out-the-window view. This requires only a near-field obstacle sensor system as presented in Sec. 2.2.6.1. By contrast, the specific challenge of a fully virtual cockpit — as in study III & IV — is that the VR-HMD has to show everything the pilot must see, whereas current solutions with PMDs or transparent HMDs present a virtual world that is used in addition to the actual out-the-window view.[15] This means the data sources must be able to entirely replace the non-available out-the-window view. The pilot completely relies on the data presented on the HMD; anything that is not captured by the data sources, cannot be seen by the pilot.

To reach this goal, a class 1 or 2 DVE system as defined by the NIAG will be required (cf. Sec. 2.2.4). The application of different data sources increases the reliability, improves the accuracy, and enables operations in various kinds of DVE. Further, the data sources must cover a wide angular extent of the environment, preferably 360°. Industry and research institutions are already working on solutions that go in that direction. The Elbit Brightnite [63] offers an array of multi-spectral uncooled IR and CMOS sensors providing $200° \times 90°$ FOV for night operations (see Fig. 3.17a). Probably the most advanced system is currently researched by the U. S. Army. It uses five cooled and three uncooled IR sensors, one lidar, one mid-resolution radar, and four low-resolution "bumper" radars [291]. Figure 3.17b illustrates the mounting of the sensors, which capture the environment all around the helicopter.

Very capable hardware is needed to transfer and process the tremendous amount of data in real time. Further, advanced computer vision algorithms are required to extract the relevant information from imaging and 3-D sensors and to fuse it with offline databases [48, 59, 170, 272].

In summary, a fully virtual cockpit poses significant challenges to the data sources for the synthetic external view. Currently, no sensor system that enables an ultimate, all-embracing virtual cockpit for all scenarios and flight phases is available. Nevertheless, solutions for specific use cases (e.g. Elbit Brightnite for night operations) have already been developed and more capable systems are realized as research prototypes. Their evolution in recent years gives rise to optimism that the required data sources will become available.

[15] Although it must be kept in mind that the value of the natural vision can be very little in DVE.

(a) Elbit Brightnite wide FOV sensor system [63].

(b) Sensor setup tested by the U. S. Army [291].

Figure 3.17 – Examples of state-of-the-art advanced sensor systems.

3.3.5 Technology Readiness, Cost & Certification

The proposed virtual cockpit is a radically new approach for future flight decks. It involves a complex system of many critical modules from real-world sensing to the generation of a completely virtual HMI. When all the discrete challenges stated above are solved, it will be the final challenge to combine these technologies into a feasible avionics system.

The data processing and presentation will definitely require significantly more computing power than is available on current aircraft. Further, all methods and technologies need to be ruggedized for usage on helicopters. Due to their criticality, all components must fulfill the highest reliability criteria and provide multiple redundancy in case of failure. In summary, this will result in high costs. Nevertheless, such a system can only be successful if the SWaP-C [3] requirements — size, weight, power, and cost — can be kept within an acceptable range. Thus, these penalties must be outweighed by benefits like an operational credit or increased safety.

Raising the technology readiness from a proof of concept to a flight-proven and certified system will definitely be a long path. In parallel, safety issues need to be addressed and concepts of operation need to be implemented. The few operational credits for conventional vision systems (see Sec. 2.2.3) show that the certification of an even more complex virtual cockpit will require significant effort. Nevertheless, it seems not impossible once the technological challenges are met. The certification effort will also vary with the degree of cockpit virtuality and the intended use case. The virtual instrument solution developed in Chapter 5 seems to be certifiable in the short or medium term (see Sec. 5.4.2 for a thorough discussion). Predictably, the first systems will be used for short special missions that would not be possible at all without such technology. The ultimate fully virtual cockpit will certainly require more time and effort.

3.4 Application to Helicopter Operations in Offshore Wind Farms[16]

To further explore the described concept of a virtual cockpit, the theoretical framework must now be applied to a specific use case. Helicopter offshore operations (HOFO) are typical missions where various kinds of DVE often occur. This section summarizes the author's analysis of these scenarios, describes specific maneuvers in offshore wind farms, and states the major challenges of flying offshore. The results of this analysis are then used to develop concrete implementations of a virtual cockpit that tackle the identified challenges. Further, the described maneuvers are later used to evaluate the developed display concepts in simulator experiments.

3.4.1 Helicopter Offshore Operations in General

HOFO are defined as "operations which routinely have a substantial proportion of the flight conducted over sea areas to or from offshore locations" [83]. The term "offshore location" includes, but is not limited to: helidecks, shipboard heliports, and hoisting areas on vessels or renewable-energy installations [82] (see Fig. 3.18). These operations are usually conducted for the purpose of: "(a) support of offshore oil, gas and mineral exploration, production, storage and transport; (b) support to offshore wind turbines and

[16] Parts of this section have been published by the author in [77, 79].

other renewable-energy sources; or (c) support to ships including sea pilot transfer.” [82]

(a) Agusta Westland AW139 landing on offshore helideck surrounded by various obstacles [p].

(b) Helihoist platform on top of a wind turbine nacelle [q].

Figure 3.18 – Examples of offshore locations where helicopters usually operate.

Offshore flights for the oil & gas industry have been conducted for over 50 years, whereas the offshore wind energy sector is a relatively new and fast-growing business. In both sectors, helicopters play an important role during both construction and operation. Due to their flexibility, their hover capability, and their higher speed compared to ships, these aircraft perform important tasks like HEMS, passenger transfer, and freight flights. Compared to the oil & gas sector, helicopter operations in wind farms present several specific challenges for pilots, for instance, hoist maneuvers to drop off workers onto wind turbines.

The harsh and demanding nature of offshore scenes creates high requirements for both crew and equipment. It also regularly leads to incidents and accidents. Nascimento et al. [217] identified more operational (e.g. pilot- or weather-related) than technical causes for worldwide offshore accidents. Further, the night-time accident rates were found to be significantly increased. This leads to the conclusion that advanced flight guidance solutions may help to reduce accident rates. Especially the application of modern vision systems could improve the pilots’ situational awareness. Within the national joint research project AVATAR, the author analyzed the specific challenges of such operations using an online survey and a structured interview with pilots and operators [78]. This dissertation summarizes the most relevant findings. The author’s full report is published in [79].

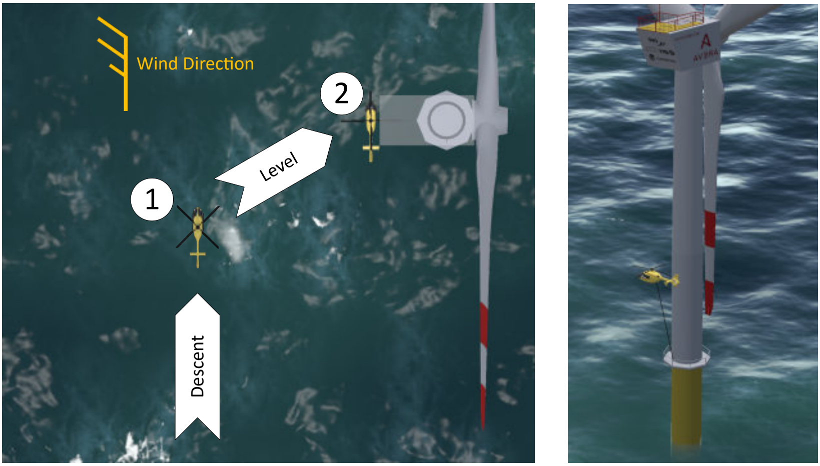
3.4.2 Specific Offshore Maneuvers

The two most common maneuvers in offshore wind farms are landing on an offshore helideck and hoisting at a wind turbine. In general, the en-route flight to the scene is described as not critical while the hoisting or landing task itself is seen as the most challenging part of the operation.

Platform Landing The interviewed pilots explained that they manually fly the final approach from an imaginary gate about 0.75 NM out to a landing decision point. With the used helicopters, the landing decision point is located a few feet above and laterally offset to the helideck to avoid a potential collision in case of an engine failure. From there, they land sideways. Other helicopter types are flown straight-in. Approach and landing are always conducted by the pilot sitting on the side of the helideck because the landing spot is hardly visible from the other seat. If at all possible, the whole maneuver is flown with headwind. Pilots report that the high pitch during the deceleration phase restricts their view of the desired landing spot. As can be seen in Figure 3.18a, the helideck is often surrounded by various installations, which increases the risk of a collision. Additionally, as the approach direction is predetermined by the headwind requirement, such obstacles can complicate the landing procedure and lead to side- or backwards maneuvering before touchdown.

Wind Turbine Hoisting Many different types of hoist maneuvers are conducted offshore. Regularly, persons are winched at predefined hoist areas, which can be located on ships, platforms, or wind turbines. In HEMS scenarios, however, the hoist is used wherever necessary, for example to rescue people out of the water. Since the pilots are not able to see the person to be picked up or set down under the helicopter, the hoist operator plays an important role. The pilots keep the aircraft in a stable hover while the hoist operator acquires visual contact with the person and directs the cockpit crew by voice commands. Especially with moving targets like ships or persons in the sea, this procedure can be cumbersome and requires special training and good crew coordination. Airlifting to wind turbines is usually performed at a helihoist platform on top of the nacelle (see Fig. 3.18b). In case of emergency, the crew can also hoist at the lower access platform of a wind turbine. Hoisting at this so-called transition piece is a special maneuver, which is only conducted for rescue and if the conventional access at the nacelle is not possible.

Figure 3.19 illustrates this transition piece hoisting in detail. The pilots approach the wind turbine in head-wind direction. They descend to position ① such that they can see the wind turbine tower on their front right. From there, they hover sideways to the desired hover position ②. At that point, the wind turbine tower is located at the pilot's 3 o'clock position. Now, the hoist operator at the right cabin door and the personnel on the wind turbine conduct the rescue following a trained procedure. A Hi-Line is used to pull the hoist cable towards the wind turbine. During the whole procedure, the pilot must hold a stable hover most of the time but also has to change the position a few times.



(a) Top view showing flight path and hover position ②. **(b)** 3-D view.

Figure 3.19 – Hoist operation at the transition piece of an offshore wind turbine. It requires hovering very close to the turbine tower (own figures).

The lateral position of the helicopter must always stay within a certain range: For safety reasons, the minimum clearance between the main rotor tips and the wind turbine tower is 5 m, which is about half a rotor diameter for the Airbus H135. The maximum distance is defined by the fleet angle limit of the hoist system. In other words, the hoist cable may not be deflected more than a certain angle to the side. According to the surveyed operators, this results in about 5.7 m maximum clearance at the target hover height. The interviewed pilots indicated that they have problems estimating the clearance since the white tower appears like a large, texture-less surface. Therefore, hand-held laser distance meters are often used by the hoist operator to guide the pilot.

3.4.3 Challenges of Offshore Flying

In summary, two major challenges for the examined offshore operations were identified by the author. These are typical DVE issues:

1. lack of usable outside visual cues,
2. restricted external view caused by non-transparent parts of the airframe and/or the pilot's inappropriate viewpoint.

Lack of Usable Outside Visual Cues Onshore pilots flying under VFR can orient themselves by looking out of the window. The horizon, nearby objects, and terrain features help them judge their position and attitude. The offshore environment, however, offers only a few usable visual cues. Firstly, only a few fixed objects exist. Secondly, usable optical flow and ground texture cues are rarely available from the water surface. Caused by its own movement, the sea often provides more misleading than valuable information. Thirdly, this shortage of external references is often even aggravated by weather conditions that further degrade the view and obscure the horizon. Finally, the rapid changes of the weather as well as darkness during night-time make missions even more complex. The lack of cues can lead to false height, distance, or attitude perception and — in the worst case — result in spatial disorientation.

Restricted External View The limited sight from the pilot's seat appears to be relevant in many scenarios. It is often caused by non-transparent parts of the aircraft structure but is in certain scenarios also a result of the pilot's inappropriate viewpoint. In general, pilots can hardly see what happens below, above, and behind the helicopter. Even the forward and sideward view is severely restricted. The front windows are relatively small and the instrument panel covers a large amount of the pilots' forward view. This leads to a poor view of the landing spot during approaches with high pitch angle. Related issues are the control of separation from obstacles located at non-observable places and the missing direct view of persons being hoisted. These problems can partly be mitigated if a hoist operator is aboard. They can keep their eyes out and instruct the pilots. However, the multi-stage process from the hoist operator's information perception to the pilot's final control input is time-consuming and error-prone. Furthermore, the hoist operator's sight is also limited as they usually sit at the cabin door on one side of the helicopter.

3.5 Recapitulation & Transition to Practice

This chapter dealt with the question of how modern HMD technology can be used to create a future virtual cockpit (cf. RQ 1-A). To approach this question, the author developed the *virtual cockpit continuum* — a theoretical framework that defines different variations of a virtual cockpit. Depending on the degree of virtuality, a different HMD type is used: optical see-through HMDs for less virtual solutions and immersive HMDs for more virtual approaches. The view domains and data flows of these partially and fully virtual cockpits were sketched and compared via system structure graphs.

As next step, the author addressed RQ 1-B as he explored the qualities and limitations of using an immersive HMD and compared them to the established solutions. Thereby, the following main potentials of a virtual cockpit were identified:

- full control of what the pilots see with an immersive HMD
- opportunity to create a flexible, task-adaptable virtual HMI, gradually replacing the inflexible conventional flight deck
- real-world-aligned, unobstructed, wide-angle view of the external scene with head-coupled viewing direction
- versatile options for the visualization of a computer-generated external view that exactly matches the pilot's needs
- HMD-related advantages like sophisticated depth cueing, blocked real-world influences, wide display field of view, et cetera

On the other hand, the author also detected several challenges for the realization of a virtual cockpit:

- limited replication of the real world on the display
- need for specific methods to interact with real and virtual environment
- user-centered issues like ergonomics and cybersickness
- need for advanced and reliable data sources like aircraft-mounted sensors and pre-stored databases
- high system complexity, cost, and certification effort

The presented virtual cockpit continuum is a theoretical framework and the compiled list of potentials and challenges is also — intentionally — held rather abstract and general. The presented concept offers many opportunities and great freedom for the actual implementation. The look of a concrete virtual cockpit strongly depends on the scenario it is designed for, i.e. flight task, DVE type, et cetera. By the same token, the actual relevance and effect of a certain potential or limitation can vary from case to case.

Therefore, the remainder of this thesis will put the theoretical concept into practice by developing and assessing concrete virtual cockpit implementations for defined DVE scenarios. As a starting point, this chapter analyzed helicopter offshore operations, described specific maneuvers in wind farms, and identified two major challenges to be tackled by a virtual cockpit: 1) lack of usable outside visual cues, and 2) restricted external view caused by non-transparent parts of the airframe and/or the pilot's inappropriate viewpoint.

Chapters 5–7 will address the identified DVE challenges and thereby focus on the following potentials of a virtual cockpit:

- Chapter 5 will show how the freedom of a virtual HMI can be used beneficially by implementing flexible, task-adaptable virtual cockpit instruments — this builds upon the potentials from Sec. 3.2.3.
- Chapter 6 will demonstrate how one can make use of the properties of an immersive HMD to create a virtual external view that provides more valuable information and visual cues than its real-world counterpart — this substantiates the potentials from Sec. 3.2.2.
- Chapter 7 will present how the full control of the pilot's view can be used to develop non-conventional ego- and exocentric views that solve the DVE issues regarding fuselage-restricted cockpit view and adverse pilot eye point — this combines several potentials from Sec. 3.2.1–3.2.3.

Chapter 4

Evaluation Environment[1]

Before the virtual cockpit concept could be put into practice, the author had to build up a suitable prototyping and evaluation infrastructure at DLR's Institute of Flight Guidance. This chapter describes the new XR Simulator (XR-Sim) — where XR acts as a placeholder for augmented, virtual, and mixed reality (AR, VR, MR; see Sec. 2.1.1). It defines the goals for the development of the XR-Sim, explains the system architecture and selected implementation details, and finally presents the possible simulator configurations for human factors evaluations. The following Chapters 5–7 will refer to this chapter when the individual simulator setup of the evaluation studies is described.

4.1 Goals for the Development of the Simulator

The XR-Sim was developed with the following three objectives in mind:

Enable Fast & Easy Prototyping and Testing A major goal was to create a development environment for display software that allows for fast and easy symbology prototyping and testing. For research purposes, it is crucial to have a toolbox that allows the researchers to rapidly realize and test their symbology ideas. This includes both software and hardware.

[1] Parts of this chapter have been published by the author in [77].

Target Consumer-Grade and Professional HMD Hardware Based on the "easy to use" requirement above, the second major goal was to integrate various consumer-grade AR and VR goggles. Besides the lower hardware costs, such devices usually require less integration effort and can be used in an office or low-fidelity simulator setup. Expensive flight-certified HMDs are often less available and more complicated to use. Consequently, researchers can employ consumer-grade devices to develop and test display concepts within an easy-to-use environment. After that, the new software should be easily portable to flight-certified hardware for further evaluations.

Integrate with Existing Simulation Infrastructure Finally, the new XR-Sim must be integrated with the simulation soft- and hardware of DLR's already existing simulators. This includes — for instance — the connection to flight simulation programs like X-Plane as well as the communication with legacy display code. Also, the existing professional JedEye HMD by Elbit Systems Ltd. and other cockpit hardware should be supported.

4.2 Implementation of the Simulator

To achieve these goals, the game engine Unity [316] was chosen as the software tool for implementing the HMD graphics. Unity comes with an integrated development environment that simplifies the process of generating the display symbologies and scenes for human factors evaluations. With a few mouse-clicks in the graphical 3-D editor, the user can create or import new objects and place them within a 3-D world. Moreover, the programmer can write C#-scripts to add functionality. Being a game engine, Unity comprises many readily available modules and packages that strongly facilitate the fast implementation of virtual environments.

An important plus is that Unity's XR module hides hardware-specific differences between the AR/VR goggles from the programmer. Thus, no changes to the display code are required when the display hardware is changed. Unity supports many consumer-grade devices like Oculus Rift, HTC Vive, Microsoft HoloLens, or Metavision Meta 2. This makes it an attractive choice for the development of software targeting such devices.

Alternatively, other engines like the Unreal Engine [318] could be used. If one does not want to depend on a game engine, one could build a custom-made engine based on Khronos' OpenXR standard [229]. It defines an application programming interface which serves as a layer between the application and the various XR platforms like SteamVR, Oculus, Windows Mixed Reality. Thereby, OpenXR enables straightforward development of cross-platform XR applications. A self-built engine creates great flexibility. Nevertheless, this was no option for this work because the freedom comes with the enormous effort needed to develop all other required modules that a game engine like Unity has readily available.

4.2.1 System Architecture

Figure 4.1 shows the architecture of the assembled XR-Sim and gives an overview of the hardware components, the various software applications, and the data flows between the modules. As described later in Sec. 4.3, the various modules of the simulation environment can be composed according to the requirements of the actual study. Here, an all-embracing setup with all available elements is presented.

The heart of the system is a workstation PC running the *XrSimDisplay* application, the *XrSimControl* module, and legacy display software like a PFD. The HMD unit is connected to the display software of this *XR Simulator PC*. The *Flight Simulation PC* computes the aircraft state based on the user inputs from the connected active force feedback flight controls by Brunner Electronics AG [28]. Finally, another separate PC handles the recording of aircraft state and head-tracking data. These five hardware modules represent the minimal, standalone configuration of the XR-Sim. Depending on the individual study requirements, one can couple this setup with a conventional helicopter simulator including an outside vision projection system and a cockpit shell.

The *XrSimDisplay* program is the centerpiece of the XR-Sim. It is developed with the game engine Unity and generates all graphical content for the HMDs. All symbology concepts described in Chapters 5–7 are implemented in the *XrSimDisplay* app. The communication with the HMD is realized by Unity's XR module, which supports a wide range of commercially available VR and AR goggles. It receives the head-tracking data (dashed blue lines) from the HMD and delivers the rendered stereo image back to the goggles. Additionally,

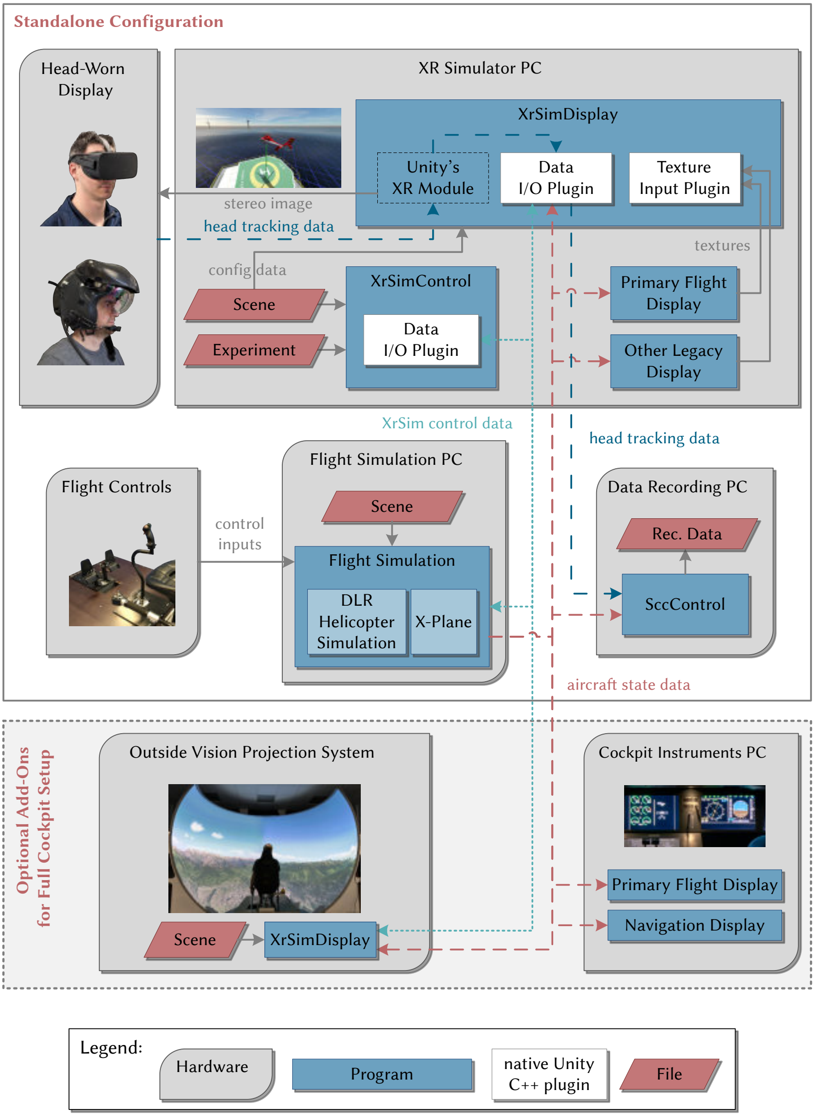


Figure 4.1 – Architecture of the simulation environment "XR-Sim", which the author implemented to assess his virtual cockpit (own illustration).

DLR's flight-certified HMD — the Elbit JedEye — can be connected via in-house software. A custom-made texture input plugin enables the integration of legacy display code into the Unity environment. This allows the author to show existing PFD or other legacy display implementations within the virtual scene. Technical details of this mechanism are explained in Sec. 4.2.3. A data I/O plugin provides interfaces for the communication with other simulator modules. Currently, the software is run on a workstation PC equipped with an NVIDIA GeForce GTX 1070 video card.

The *XrSimControl* software manages the setup and procedure of an experiment. It reads the experiment and scene configuration from two files and sends commands to all involved applications. Furthermore, it provides a Unity-based graphical user interface for the experiment leader. As sketched by the dotted blue lines in Fig. 4.1, this module communicates with several involved programs to manage the correct procedure of the experiment. For instance, when the experiment leader starts the next trial, *XrSimControl* tells the display modules to load the appropriate scenario. After re-confirmation, it requests the flight simulation and the recorder to start the run.

The flight simulation computes and transmits the current aircraft state (red lines) to all display applications and the recording PC. To date, the XR-Sim provides two options for the flight simulation. First, the commercially available software X-Plane can be used to simulate the behavior of several existing helicopter types. Second, a custom-made model of DLR's EC135 research helicopter with advanced flight control modes is available (details see Sec. 4.2.2).

Aircraft state, head-tracking, and control data are exchanged between the modules via shared memory and Ethernet using the user datagram protocol. For compatibility, the XR-Sim adopts the same data interfaces that are used by the existing HMD and flight guidance applications in DLR's high-fidelity simulators and in the research helicopter. In *XrSimDisplay/-Control*, this data I/O module is implemented via Unity's native plugin mechanism. This allows the author to call existing C++ functions — defined in externally compiled dynamic-link libraries — from C#-based Unity scripts.

As mentioned above, the so far described standalone configuration of the XR-Sim can be integrated into a conventional cockpit simulator like the Generic Experimental Cockpit (GECO) at DLR's Institute of Flight Guidance. The GECO is a fixed-base simulator replicating the Airbus A350 instrument panel within an A320 shell. For helicopter studies, it can be equipped with rotorcraft flight controls and the JedEye HMD. The GECO's collimated vision system makes the pilots perceive the out-the-window view in "infinite" optical distance, like in reality. This is a crucial feature for the integration of flight-certified HMDs because their optics also project the image at optical infinity. It allows the pilot's eyes to simultaneously focus on the real world and the superimposed symbology, without re-accommodation. The GECO projection system has three channels with a resolution of $3 \times 2560\,\text{px} \times 1600\,\text{px}$ and provides a total FOV of $180° \times 40°$.

In this full cockpit configuration, every outside vision PC runs an instance of the *XrSimDisplay* application — configured to generate the scenery on the projection screen. Additionally, a *Cockpit Instruments PC* generates the graphics for the PMDs. While this is not needed for a fully virtual setup with opaque VR goggles, it is essential for AR applications and for experimental baseline testing with a conventional cockpit. Detailed descriptions and images of the various XR-Sim configurations are presented in Sec. 4.3.

4.2.2 Flight Simulation

The XR-Sim provides two options for the flight simulation: the commercially available flight simulator X-Plane by Laminar Research [353] and an in-house model of DLR's research helicopter.

X-Plane is an integral part of several simulators at DLR's Institute of Flight Guidance. A custom-made add-on, which uses X-Plane's plugin architecture, provides specific functionalities and integrates the flight simulation with other modules. *XrSimDisplay* implements the available interfaces to connect to X-Plane. For this work, X-Plane 11.41 is used with a third-party model of a Eurocopter EC135 provided by rotorsim [57]. With the help of the rotorsim developer and DLR's test pilots, rotorsim's "EC135 Pro" model was further optimized to provide realistic handling characteristics.

In addition to the simulation of current helicopters, it is crucial for this research to also experiment with next-generation rotorcraft featuring modern flight control systems (FCS). Therefore, the XR-Sim integrates a simulation of DLR's research helicopter FHS, a highly modified EC135 with a full-authority fly-by-wire/fly-by-light control system [138]. Its model-based FCS was designed to ease the piloting task in order to reduce workload and enhance safety. To achieve that goal, DLR's Institute of Flight Systems developed a system that offers modern flight control laws with different levels of automation [117].

A pilot flies a helicopter by manipulating its three flight controls: cyclic stick (right hand), collective lever (left hand), and pedals (feet). In conventional helicopters, the pilot (more or less) directly controls the movement of the main and tail rotor blades with these input devices (the former via the swashplate). The coupling of the axes requires coordinated inputs in all axes to safely fly the aircraft. Modern FCS simplify that. All upper control modes have in common, that the pilots do not directly steer the rotor blades anymore. Instead, they issue higher-level commands like "decelerate while holding the altitude", "do a coordinated turn", or "move sideways with a certain translational rate". The FCS translates these commands into the required actuator movements for the different axes.

DLR's command model provides several command types for the four flight control input axes. These are combined with various hold functions. Table 4.1 gives an overview of the command modes used in this work. A common mode for the longitudinal and the lateral cyclic axis is *rate command, attitude hold* enabling the pilots to set a pitch or roll rate. Another option for those axes would be *attitude command, attitude hold.* This allows the pilot to directly command a pitch or roll attitude, while a neutral stick position makes the helicopter return to trimmed attitude. *Acceleration command, airspeed hold* in the longitudinal cyclic axis is a mode where each stick deflection corresponds to a certain, constant acceleration. In neutral stick position, the current airspeed will be held. Finally, an advanced cyclic mode for low-speed maneuvering is *translational rate command, position hold.* If the pilot releases the cyclic stick, the helicopter will automatically perform a stable hover at the current position. By moving the stick sideways, back-, or forwards, the aircraft will horizontally move in the corresponding direction.

For the pedals, two control laws are available: *rate command, direction hold* and *turn coordination.* As the name implies, the former enables the pilot to command a yaw rate while the FCS holds the current flight direction if the pedals are not deflected. In *turn coordination* mode, the FCS automatically produces sideslip-free turns. Selecting *vertical velocity command, height hold* for the collective enables the pilot to directly command a vertical speed via the collective. This is — like any other of the presented command modes — uncoupled from other inputs, which means that if the collective remains in a

Table 4.1 – Command modes used in this work (based on [117]).

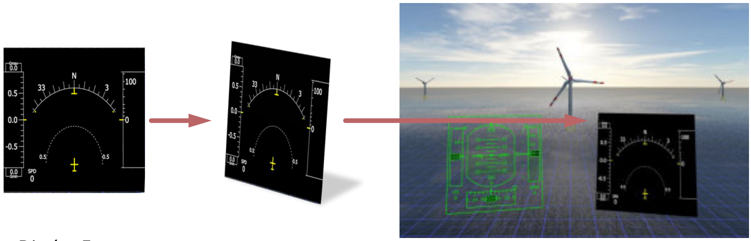
Input Axis	Command Mode	
Cyclic longitudinal	RCAH	rate command, attitude hold
	ACAH	attitude command, attitude hold
	AcCAsH	acceleration command, airspeed hold
	TRCPH	translational rate command, position hold
Cyclic lateral	RCAH	rate command, attitude hold
	ACAH	attitude command, attitude hold
	TRCPH	translational rate command, position hold
Pedals	RCDH	rate command, direction hold
	TC	turn coordination
Collective	VVCHH	vertical velocity command, height hold

neutral middle position, the helicopter stays at the current altitude regardless of any cyclic stick inputs. For more details and implementation specifics please refer to Greiser et al. [117].

The presented command types can be manually chosen or automatically adapted during flight. Tying the automation to the airspeed allows — for example — the definition of a "high-speed mode" where speed and turns can be easily commanded via the cyclic in AcCAsH and ACAH law, while *turn coordination* and *height hold* is enabled. As the aircraft slows down, the command modes change to a "low-speed mode" and finally to a "hover mode". Being in the latter, the pilot can horizontally move the helicopter in both axes via the cyclic in TRCPH mode. Simultaneously, the pedals control the turn rate around the yaw axis (RCDH) while the collective is used to manage vertical position changes (VVCHH). The studies presented in this dissertation did not apply automatically varying control laws but instead had manually set modes that did not change during flight.

4.2.3 Integration of Legacy Display Code

Section 3.2.3 envisaged virtual instruments acting as virtual flat-panel screens within the computer-generated 3-D world. As the graphics of these instruments have already been implemented for conventional cockpit monitors, the



Display Frame (OpenGL Application) | Textured Quad | Final Scene with Virtual Instruments (Unity)

Figure 4.2 – Integration of OpenGL-rendered instruments in an offshore environment, created in the game engine Unity (own illustration [237]).

author wanted to re-use the existing OpenGL code without re-implementing the displays again within the Unity game engine. To do so, the legacy source code was modified to render into a framebuffer target, which is then transferred into a shared memory. A texture input plugin in *XrSimDisplay* reads this pixel data and updates a textured quad element. This can be freely placed in the Unity scene and represents the virtual cockpit instrument. The process is illustrated in Fig. 4.2. Implementation details are described in [236, 237]. Although the transfer of this 2-D texture introduces small latencies, this lag is not noticeable by the user. Figure 4.1 sketches the method with a PFD and another legacy display program generating two virtual instruments for *XrSimDisplay*. This mechanism forms the basis for the further development of the virtual instruments in Chapters 5 and 7. It enables the concept development on AR and VR glasses as well as the subsequent final evaluation on professional HMDs with the same code base without porting effort.

4.2.4 Head-Mounted Display Specifications

One of the development goals for XR-Sim was to support a wide range of consumer-grade and professional HMDs. Owing to Unity's XR module, many devices can be used with minimal code changes. So far, the Oculus Rift CV 1 and the HTC Vive Pro VR goggles as well as the Metavision Meta 2 AR glasses have been used. The flight-certified Elbit JedEye HMD is presently operated via legacy OpenGL/C++ software. After porting all existing symbol sets, Unity could also generate the graphics for the JedEye.

(a) Oculus Rift CV1 **(b)** Elbit JedEye

Figure 4.3 – HMDs used for the virtual cockpit evaluations.

All experiments presented in this dissertation were conducted with two headsets: the Oculus Rift CV 1 and the Elbit JedEye. Figure 4.3 shows these devices and Table 4.2 lists their technical specifications. The Oculus Rift is a non-see-through VR-HMD while the JedEye is an optical see-through AR device. Both are binocular systems featuring one display per eye. The VR headset has full-color OLED image sources whereas the LCDs of the JedEye are monochrome green only. Additionally, the Oculus displays have a higher refresh rate. The stereo image created by the Oculus Rift has a resolution of 1080×1200 pixels per eye and covers approximately 110° diagonal FOV. This results in an angular pixel density of around 13.8 ppd [163].[2] In comparison, the Elbit JedEye offers around 27 ppd[2] having a total FOV of $80° \times 40°$ with $2200\,\text{px} \times 1200\,\text{px}$ resolution ($1920\,\text{px} \times 1200\,\text{px}$ per eye, 60° binocular overlap).

Both systems realize fast and accurate head pose measurement. The Oculus Rift applies an external optical sensor that detects several infrared LEDs embedded in the goggles. The JedEye features an electromagnetic tracking unit mounted onto the cockpit structure. An inertial measurement unit inside both HMDs complements the external trackers.

[2] This is only an approximate value because the optics do not distribute the pixels equally over the FOV and the individual lens to eye distance influences the involved parameters.

Table 4.2 – Technical specifications of the HMDs used for the virtual cockpit evaluations [61, 86].

	Oculus Rift CV1	Elbit JedEye
Type	occluded/non see-through	optical see-through
Ocularity	binocular	binocular
Color	full-color	monochrome green
Field of View	≈110°[a]	$80^\circ \times 40^\circ$
Resolution (per eye)	1080×1200	1920×1200
Display Type	OLED	LCD
Refresh Rate	90 Hz	60 Hz
Head-Tracking	optical outside-in	magnetic outside-in
Data Interfaces	USB 3.0, HDMI 1.3	SDI, DVI, RS-170, RS-343
Weight	≈0.5 kg	≈2.3 kg

[a] Depends on individual lens to eye distance.

The JedEye is significantly heavier than the Oculus, which can mainly be attributed to its application purpose. It is integrated into an aviator helmet and must fulfill crash-safety requirements, which — of course — adds weight. Also, an indoor consumer device does not have to be as ruggedized as military helicopter equipment.

Both systems belong to very different domains and target very different application scenarios: consumer VR vs. flight-certified AR. Thus, one should be cautious about directly comparing their specifications and judging about which one is better. For instance, JedEye's 80° FOV is unmatched for a flight-certified see-through HMD, while for VR-HMDs 110° is an average FOV.

4.3 Setup Options for Human Factors Studies

Owing to its modular architecture, the XR-Sim can be used in different ways, not only for the development of a virtual cockpit. Table 4.3 lists the configurations that are currently available for experiments and demonstrations. The six possible modes are classified into two groups. Both groups contain configurations where either the standalone or the full cockpit version of the XR-Sim is needed. Also, optical and video see-through AR/MR glasses as well as fully immersive VR goggles are used in either group. The first group contains configurations where the HMD is used as simulation equipment. This means that the display device is applied only in the simulator to simulate selected objects which would be part of the real world in real flight. By contrast, the second cluster comprises XR-Sim modes where the HMD is used as an actual assistance system to be used by the pilot in real flight. These latter modes reflect the whole virtual cockpit continuum, from a conventional cockpit with state-of-the-art optical see-through HMD (mode IV) via a partially virtual cockpit (V) to a fully virtual cockpit (VI).

Table 4.3 – Current XR-Sim configurations for human factors evaluations.

	XR-Sim Mode	Sim Config.	HMD Type
HMD as simulation tool:			
I	VR-simulation of conventional cockpit	standalone	VR
II	AR-emulation through VR	standalone	VR
III	AR-based simulation of additional objects	full cockpit	AR/MR
HMD as assistance system:			
IV	State-of-the-art see-through systems	full cockpit	AR
V	Partially virtual cockpit	full cockpit	MR
VI	Fully virtual cockpit	standalone	VR

In the first configuration, the XR-Sim serves as a replacement for a conventional cockpit simulator. The pilot wears VR goggles like the Oculus Rift, which create a fully immersive visual environment. The VR display shows both a virtual representation of the flight deck and the out-the-window view. With the simple setup depicted in Fig. 4.4a, part-task studies or procedure training can be conducted without the need for an outside vision system, real cockpit hardware, or an aircraft cell. The whole evaluation scene is provided by the VR goggles. As described in Sec. 2.1.5.1, such an approach is often found in the literature. For instance, Oberhauser et al. [226] apply an advanced VR setup in the early phase of the cockpit design process at Airbus. As discussed in Sec. 3.3.2, enabling the pilot to intuitively interact with the virtual HMI poses a major challenge in this setup.

With a similar standalone VR setup, the author can also emulate see-through displays like HUDs or AR-HMDs. The VR display shows the cockpit and the

(a) Pure VR setup with goggles and controls only [70, 72].

(b) Exhibition setup with additional external monitor for spectators (here at ILA Berlin 2018).

Figure 4.4 – Standalone VR setups which are flexible and easy to transport.

out-the-window view as well as the overlaid AR-symbology. In other words, the VR glasses are applied to simulate the pilot's view through a conventional, see-through HMD. This XR-Sim mode II is applied for the first evaluation study described in Chapter 5. Also, Schmerwitz et al. [266, 267] use such a simple part-task setup to evaluate a conformal landing symbology for DVE. Of course, this approach has some implications. For instance, the optics of VR goggles cannot create a collimated image like flight-certified HMDs, which can show symbology at the visual depth of the out-the-window view. Nevertheless, the VR setup is very convenient for concept studies.

Finally, one can use an AR/MR-HMD within a real cockpit to show virtual representations of certain objects. For example, this mode III makes it possible to enhance the test environment with displays or interfaces that are physically not available in the flight deck mock-up. Similar to mode I, this setup can serve as a rapid-prototyping test bed for design concept evaluations.

The best-known use case for an HMD as assistance system is the application of a see-through HMD inside a conventional cockpit. As explained in Sec. 2.3, this is a state-of-the-art approach to helicopter flight guidance and DVE mitigation. Figure 4.5b shows this IV. mode with JedEye and GECO. It was used for the second experiment described in Chapter 5.

(a) VR experiment setup with Oculus Rift and experimenter control station [74].

(b) AR setup with JedEye and *XrSimDisplay*-based outside vision [70, 72].

Figure 4.5 – Full cockpit VR and AR setups in DLR's cockpit simulator GECO.

The main focus of this dissertation is the assessment of immersive HMDs as flight guidance system. This use case is covered by mode V and VI in Tab. 4.3. Using a VR-HMD as primary flight guidance instrument means that the pilots cannot see their surroundings. Thus, it is not necessary — in a fully virtual cockpit — to have a physical flight deck mock-up around the pilot's seat and controls (mode VI, Fig. 4.4a). Nevertheless, a conventional cockpit simulator is needed, if a video-see-through HMD is used (mode V, Fig. 4.5a), or if the VR-HMD is put on in certain flight phases only. With such a setup, the researchers can investigate not only the phase when the HMD is worn but also the transition phases when the goggles are put on and off. The studies described in Chapters 6 and 7 use this configuration.

All standalone VR configurations are independent of other simulation equipment and can be easily transported. Figure 4.4b shows the XR-Sim as it was presented at the ILA Berlin 2018 and the Paris Air Show 2019.

4.4 Recapitulation

In summary, the XR-Sim is a powerful simulation environment designed for rapid implementation and evaluation of AR- and VR-based display concepts. By using consumer-grade HMDs and the game engine Unity, the author was able to reduce hardware costs and simplify the development and testing process of new symbologies. Moreover, several techniques to integrate the Unity-based system with the hard- and software of DLR's existing simulation facilities were devised. A weakness of the current setup is that the pilot's interaction with the real and virtual cockpit environments is limited. If required for future experiments, advanced methods like finger-tracking should be integrated (see Sec. 3.3.2).

The assembled XR-Sim is now used in the following Chapters 5–7 to answer the research questions RQ 2-A and RQ 2-B by developing and assessing various realizations of a virtual cockpit.

Chapter 5

Study I & II — Virtual Cockpit Instruments[1]

As discussed in Sec. 3.2.3, an HMD-based virtual cockpit offers the HMI designer the opportunity to create a flexible and task-adaptable cockpit. The concept of virtual cockpit instruments (VCIs) promises to overcome the limitations of inflexible, head-down-time-creating panel-mounted displays (PMDs). The work presented in this chapter puts the colorful ideas of many futuristic cockpit design concepts (see Sec. 2.1.5.3) into practice as it realizes a specific VCI solution for a well-defined use case.

Nearby obstacles pose a major hazard for helicopters operating close to the ground. In Sec. 1.1, poor environmental visibility as well as the view-blocking ownship fuselage and the sometimes not optimal eye point of the pilot were identified as major reasons why obstacle collisions constitute a significant part of the accident statistics. Section 3.4.3 revealed that this is also a concern for certain helicopter offshore maneuvers.

In recent years, various obstacle awareness and warning displays (OAWDs) have been presented to mitigate these issues (see Sec. 2.2.6.1). They present

[1] Parts of this chapter have been published by the author in [54, 70, 72, 73], © 2019/2020/2021 IEEE.

a 2-D orthographic top view of the nearby surroundings as addition to the pilot's natural 3-D egocentric out-the-window view. However, a common weakness of these state-of-the-art systems is that they use PMDs. This requires the pilots to continually switch their attention between cockpit display and out-the-window view — a task that consumes mental resources, generates workload, and reduces the pilots' head-up, eyes-out time.

The overall aim of the studies I & II is to:

> Use the flexibility of an HMD-based HMI and develop a concept for a task-adapted virtual cockpit instrument presenting an OAWD that provides improved spatial awareness in scenarios where the pilots' natural view is limited.

Section 3.1 presented the different levels of a virtual cockpit, from the virtualization of certain instruments in an otherwise conventional cockpit with an AR-HMD to a completely virtual environment on a VR-HMD. Here, the author takes the first step on this path as he presents a general VCI concept and realizes this approach with state-of-the-art systems (AR-HMD, near-field sensors). Additionally, the work shows that the implemented VCI solution also works in an egocentric VR setup, which is the next level of a virtual cockpit. Later, the final study IV in Chapter 7 shows how a VCI can be integrated into a fully immersive exocentric view — the highest degree of cockpit virtuality.

The following Sec. 5.1 explains the development of various approaches to integrate and position a VCI in the virtual space around the pilot. The devised options are then assessed with two pilot-in-the-loop experiments in the XR-Sim. Study I uses a fully immersive setup with VR goggles while study II applies a flight-certified AR-HMD. Method, results, and discussion of these studies are described in Sec. 5.2–5.4. The main findings from this chapter are summarized in Sec. 5.5.

5.1 Adapting the Cockpit to the Task with VCIs

As illustrated in Fig. 5.1, a VCI can be regarded as a virtual version of a conventional cockpit instrument — created and projected into the pilot's view via an HMD. This two-dimensional virtual screen extends existing symbol sets like head-up PFDs or conformal flight guidance symbology[2] (see Sec. 2.3).

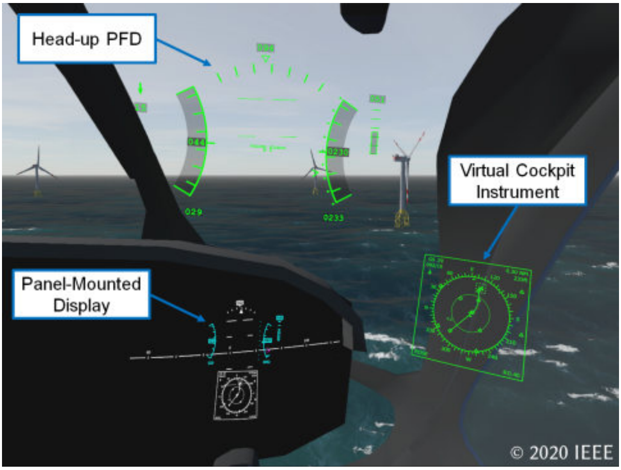


Figure 5.1 – A virtual cockpit instrument as an extension to conventional head-up symbology and panel-mounted displays — The image illustrates the pilot's view through the HMD (own illustration [70, 72]).

The development of VCIs started at DLR's Institute of Flight Guidance in 2014 with the author's student research project: "Design and Implementation of Virtual Aircraft-Fixed Cockpit Instruments" [67]. As the thesis title shows, he called them "aircraft-fixed" at this time because they were always located at a fixed position relative to the aircraft structure. Within this dissertation, the early concept is substantially expanded: New positioning options are introduced, task-adaptive positioning modes are tested, and the concept is applied to show an obstacle awareness display for confined area operations, which was developed by Ebrecht [53, 54].

[2] In this work, the VCI and other HMD symbology is drawn in green because it is developed for DLR's monochrome JedEye helmet.

5.1.1 Benefits of Virtual Cockpit Instruments

The prime advantage of VCIs is their independence from the flat panel screens of the cockpit. Conventional cockpit instruments are bound to the location, the size, and other specifications of the panel display rendering them. In contrast, a VCI can be created anywhere in the virtual space around the pilot. Its size and position can be adapted according to the requirements of the present task or flight phase. If it is currently not required, it can simply be hidden, which avoids clutter and clears the pilot's vision for the relevant information. If more display area is needed, the VCI can easily be enlarged or an additional VCI can be activated — options that are not available on a conventional flight deck with its inflexible panel display setup. The creation of additional display space is especially relevant for small helicopters like the ones often used for rescue medical services and in offshore wind farms because they have a very limited number of PMDs and cannot easily be retrofitted due to space constraints.

This great freedom and flexibility leads to the question: Where should such a virtual instrument be placed so that it creates a benefit for the pilot? Naturally, the answer to that question highly depends on the application scenario and on the actual VCI display contents. Having that in mind, the next sections first describe a general VCI framework and then apply these ideas to the specific offshore scenarios to answer the stated question — for this specific case.

5.1.2 Positioning of Virtual Cockpit Instruments

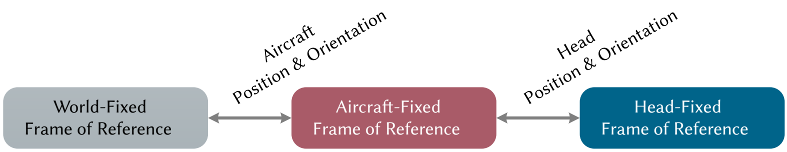


Figure 5.2 – Conversions between the involved frames of reference (own graph).

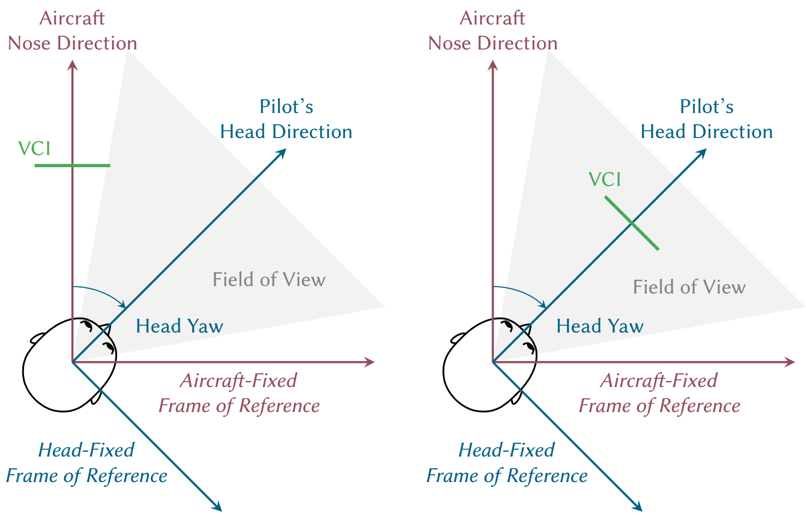
To place a VCI at a defined position in the environment around the pilot, one has to establish several frames of reference. Figure 5.2 depicts these frames and illustrates the connections between them. The *world-fixed* reference frame is rigidly attached to the environment and acts as the global frame which all other frames are defined in. The *aircraft-fixed* frame has its origin at a reference point in the ownship and follows all translations and rotations of the vehicle. Obviously, the position and orientation of the aircraft-fixed frame relative to the global world-fixed system are given by the ownship position and attitude. Finally, the *head-fixed* frame of reference is coupled to the pilot's head motion. As the pilot sits inside the aircraft, this frame is defined as a child of the aircraft-fixed system which itself moves inside the world-fixed frame. Its origin and orientation are defined by the pilot's head position and rotation relative to the parental aircraft-fixed frame. Mathematically, the described conversions between the reference frames are given by ordinary translation vectors and rotation matrices based on the position and orientation of aircraft and head. In the XR-Sim, these are implemented via Unity's scene graph.

5.1.2.1 Aircraft- vs. Head-Fixed Frame of Reference

In this thesis, the VCI is either placed in the aircraft-fixed or in the head-fixed frame. The former option implies that the VCI behaves as if it was virtually attached to the ownship — like a conventional PMD. This means that, if the pilot looks in any direction other than the VCI position, the displayed information will not be available because it will be outside of the pilot's FOV. Figure 5.3a illustrates this scenario: The aircraft-fixed VCI is positioned in forward aircraft direction while the pilot's head is turned to the right. By contrast, Fig. 5.3b shows a head-fixed VCI which follows the pilot's head movements. Thus, it is available no matter where the pilot looks at.

5.1.2.2 Position of the VCI within its Frame of Reference

The frame of reference defines the movement of the VCI relative to the surrounding scene. The next step of the VCI positioning process is to place the VCI at a certain location within that chosen frame of reference. As depicted in Fig. 5.4, this can be done in Cartesian and spherical coordinates. The conversion between the Cartesian VCI position $(X, Y, Z)_{VCI}$ and its spherical equivalent $(R, \Psi, \theta)_{VCI}$ is given by



(a) Aircraft-fixed VCI outside field of view. **(b)** Head-fixed VCI stays within field of view.

Figure 5.3 – Comparison of aircraft-fixed and head-fixed VCI — The sketches show a top view of a pilot looking to the right (own illustration[3]).

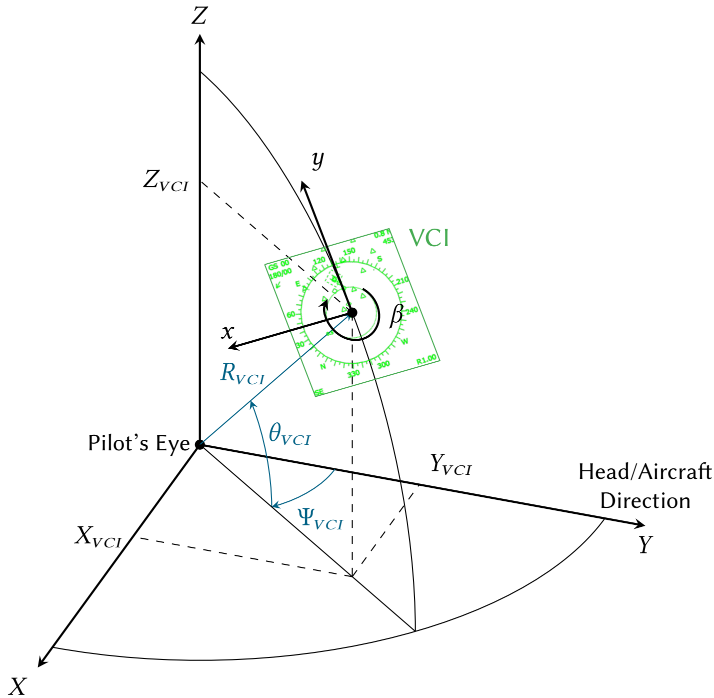
$$\begin{aligned} X &= R\cos\theta\sin\Psi \\ Y &= R\cos\theta\cos\Psi \\ Z &= R\sin\theta \end{aligned} \qquad \text{and} \qquad \begin{aligned} R &= \sqrt{X^2+Y^2+Z^2} \\ \Psi &= \operatorname{arctan2}(X,Y) \\ \theta &= \arcsin\tfrac{Z}{R} \end{aligned} \tag{5.1}$$

respectively.

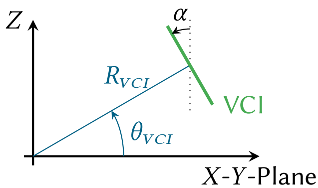
To place a VCI beside the instrument panel as in Fig. 5.1, one has to choose the following spherical coordinates in the aircraft-fixed frame: $R_{VCI} = 0.7\,\text{m}$, $\Psi_{VCI} = +34°$ (right of the helicopter's longitudinal axis), and $\theta_{VCI} = -20°$ (below the horizontal X-Y-plane of the aircraft).

Eye Rotation Zones for Head-Fixed VCIs In theory, a VCI can be positioned everywhere around the pilot ($-180° \leq \Psi_{VCI} \leq 180°$, $-90° \leq \theta_{VCI} \leq 90°$). In practice, one has to respect the limits of how far humans can comfortably turn their heads and eyes in order to reach the VCI. The literature

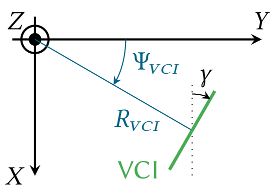
[3] Field of view not to scale; head position similar to aircraft reference point for convenience.



(a) Positioning of the VCI via Cartesian coordinates $(X_{VCI}, Y_{VCI}, Z_{VCI})$ and spherical coordinates $(R_{VCI}, \Psi_{VCI}, \theta_{VCI})$ as well as VCI roll angle β.



(b) Side view with VCI tilt angle α.



(c) Top view with VCI tilt angle γ.

Figure 5.4 – Position and orientation of the VCI within the aircraft- or head-fixed frame of reference (own illustrations).

provides several, partly nonconforming design guides [e.g. 164, 313, 315, 352]. Here, the recommendations given by Tilley [313], which agree to the U. S. military standard MIL-STD-1472G [315], are used. Figure 5.5 illustrates Tilley's zones for "easy" and "maximum" eye rotation. These are very important for the placement of *head-fixed* VCIs because those — being rigidly attached to the head frame — can only be reached by eye movements. According to the graph, a head-fixed VCI is best placed in the area below the eye level ($-30° + \frac{\eta}{2} \leq \theta_{VCI} \leq 0° - \frac{\eta}{2}$). This "asymmetric position" of the optimal zone is based on the fact that humans prefer a relaxing sight line of 15° below the horizontal sight line [313]. At best, the lateral angular position Ψ_{VCI} should not exceed ±15°.

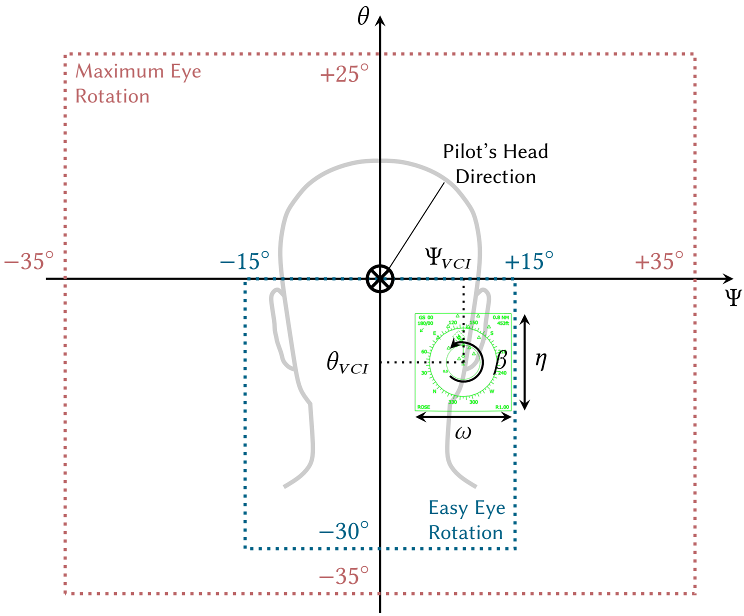


Figure 5.5 – Positioning of the VCI in the head-fixed frame of reference taking into account the human-eye rotation capabilities — The figure shows the central part of the pilot's field of view as angle-angle graph and illustrates the eye rotation zones given by Tilley [313]. Further, the VCI's roll orientation β and the angular size parameters (ω, η) are visualized (own illustration).

5.1.2.3 Orientation of the VCI

The third property that needs to be specified — besides reference frame and position — is the orientation (α, β, γ) of the VCI. As sketched in Figs. 5.4b and 5.4c, α and γ indicate the tilt of the VCI and therefore define at which angle the pilot looks at the instrument. For conventional displays, these angles are predefined by the geometry of the instrument panel. MIL-STD-1472G recommends that "display faces shall be perpendicular to the user's normal line of sight" [315]. Of course, the recommended 90° between LOS and display face is usually achieved only for the central displays, whereas the peripheral PMDs are always seen at a lower angle.

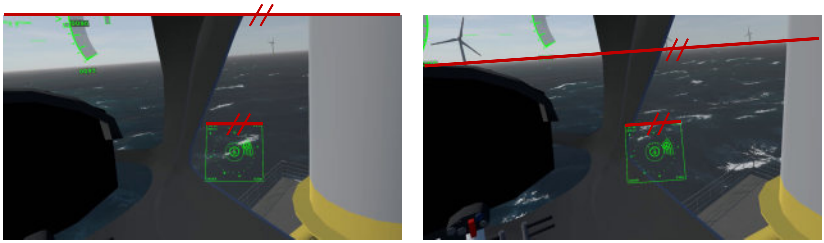
The advantage of a VCI is that it can be freely oriented and therefore fulfill the perpendicular-to-LOS recommendation no matter where it is positioned. The pilots can be surrounded by a set of VCIs, all tilted towards them. According to Fig. 5.4, this is achieved by choosing the orientation angles (α, β, γ) based on the VCI's spherical position $(\Psi_{VCI}, \theta_{VCI})$:

$$\alpha = \theta_{VCI} \qquad \beta = 0 \qquad \gamma = \Psi_{VCI} \tag{5.2}$$

Roll Orientation of Head-Fixed VCIs Hands-on tests in the simulator revealed that — in the *head-fixed* frame of reference — the VCI roll orientation β needs further consideration. The straightforward way is to set $\beta = 0$. This means that the VCI will always be rendered with the same rotation relative to the pilot's head orientation and it will always be aligned with the HMD's screen space. Figure 5.6a shows this option through the eyes of the pilot wearing the HMD.

It is obvious that such a head-aligned VCI is not aligned with the visually compelling horizon as soon as the pilot looks to the side and the helicopter is in a non-level attitude. Instead, the pilot perceives an angle between upper VCI border and horizon, which continually changes with every rotation of head or aircraft. In pre-tests, this ever-changing angle appeared to be rather disturbing — especially during low-speed maneuvers where the helicopter is agile and the pilot's LOS points to objects on the side of the helicopter.

The issue can be solved by continuously adapting β such that the VCI's upper border remains always parallel to the horizon, as sketched in Fig. 5.6b. From an implementation point of view, this implies that the required roll angle β, which is defined locally in the head-fixed frame, must be computed based on the rotation matrices defining the relations to the aircraft-fixed and the world-fixed frame, where the orientation of the horizon is defined (see Fig. 5.2 for an illustration of the involved coordinate transformations). As a result, the VCI rolls within the head-fixed HMD screen space whenever the aircraft or head orientation changes to ensure alignment with the horizon.



(a) Head-aligned VCI roll orientation. **(b)** Horizon-aligned VCI roll orientation.

Figure 5.6 – Comparison of the two options for the roll angle β of a head-fixed VCI. The red markings indicate which lines are aligned in each variant (own illustrations).

Figure 5.6 shows both roll orientation options side by side. It is important to note that — even though the variants seem to differ only little on these static screenshots — the difference becomes very noticeable when wearing the HMD with dynamic aircraft and head motions. While the horizon-alignment erases the described issues, the head-alignment seems to be superior in cases where other head-fixed symbology is presented in addition to the VCI. An example is the head-referenced PFD shown in Fig. 5.8d. This symbology is visually more compelling than the horizon. Therefore, an alignment of VCI and PFD is preferred over a horizon-aligned VCI which would cause continual relative rotations between PFD and VCI symbology elements.

5.1.2.4 Size of the VCI

The final parameter to be defined is the size of the VCI, which essentially determines the readability of the display content. As sketched in Fig. 5.5, the author decided to specify the width and height of the VCI as angular values (ω, η) since this has several practical advantages. Firstly, ω and η describe the size universally, independently of the distance R between eye and VCI. Secondly, an angular notion of VCI size can be easier related to the spherical position (Ψ_{VCI}, θ_{VCI}) and to the available FOV, which are also given as angular values. Finally, this approach allows the display designer to easily calculate the number of pixels corresponding to the respective VCI size via the angular resolution of the HMD. In doing so, one gets an objective measure for the required size of display elements based on the parameters of a specific HMD. For instance, a VCI size of $10^{\circ} \times 10^{\circ}$ on the JedEye HMD with its angular resolution of approximately 27 ppd results in 270×270 pixels for the VCI.

5.1.3 VCI Positioning Modes

The previous section showed how a VCI can be generally positioned, oriented, and sized within an aircraft- or head-fixed frame of reference. Based on that, the author developed four principal VCI positioning modes: 1) *Aircraft-Fixed*, 2) *Head-Fixed*, 3) *Mixed*, and 4) *Aircraft-Related*. Figure 5.7 sketches these modes, their respective sub-modes, and the various VCI positions that have been realized within these (sub-)modes. Figure 5.8 shows examples of how the implemented variants look to the pilot through the HMD. The following paragraphs explain the positioning modes in detail.

Aircraft-Fixed In the *Aircraft-Fixed* mode, the virtual instrument is displayed as if it was fixed to the aircraft. In other words, if the helicopter rolls, the VCI rolls with it and remains at the same position relative to the airframe. As sketched with the trapezoids in Fig. 5.7, three positions were implemented within that frame. The straightforward way is to place the VCI where a conventional cockpit instrument would be, i.e. in the panel area. Figure 5.8a shows a screenshot of this variant which is called “HDD” (head-down display). For the second position, “HUD”, the VCI is located above the instrument panel in the windshield area where a conventional HUD would be mounted. In addition to these familiar options, the HMD technology provides the freedom to place the VCI wherever it may be beneficial for the pilot’s current task. This condition is referred to as *AircraftFixed-Free*. One suitable position is right of the instrument panel as illustrated in Fig. 5.8b.

Head-Fixed The *Head-Fixed* positioning mode comprises a VCI that is attached to the head-fixed reference frame. As described above, this means that the instrument is always located at the same position within the FOV

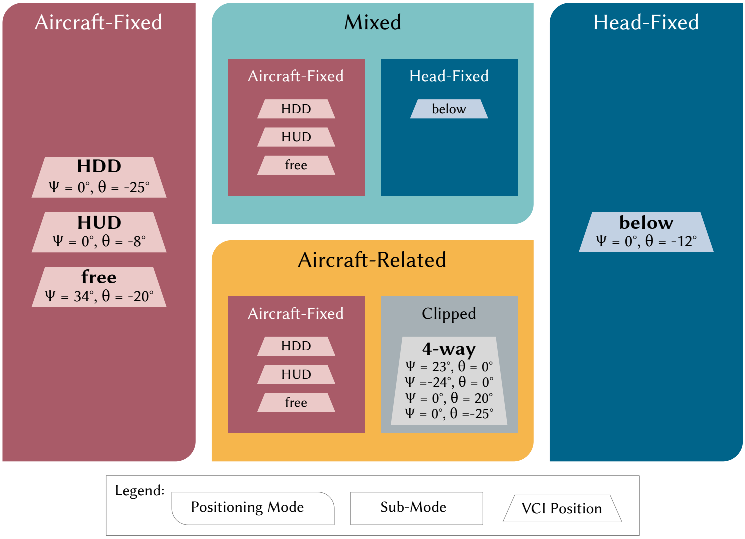
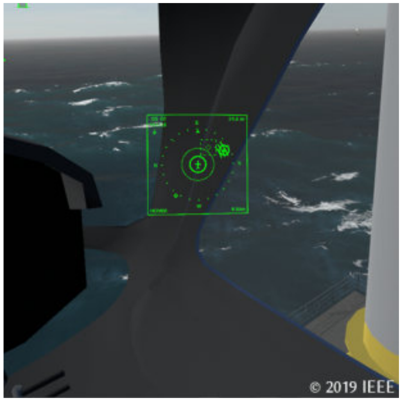


Figure 5.7 – Overview of the four VCI positioning modes (Aircraft-Fixed, Aircraft-Related, Mixed, Head-Fixed) and the respective instrument positions (Ψ_{VCI}, θ_{VCI}). Aircraft-Related and Mixed comprise sub-modes which are activated based on 1) the pilot's viewing direction, or 2) the flight phase (own figure).

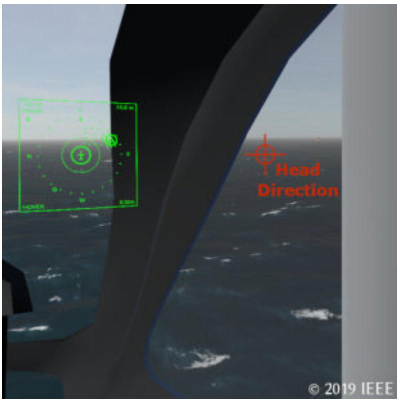
and moves with the pilots' sight as they turn their head. For this dissertation, the head-fixed VCI was always positioned centrally below the pilot's head direction (see Fig. 5.8d). As previously discussed, this is the zone that is most easily reachable by eye rotations (see Fig. 5.5).

Mixed The *Mixed* mode has two distinct states. As illustrated in Fig. 5.7, the two states (or sub-modes) are the already described modes *Aircraft-Fixed* and *Head-Fixed*. The author devised two distinct mechanisms to trigger the transition between the two states: 1) based on the pilot's viewing direction, 2) based on the flight phase. In option 1 (used in study I), the VCI has an aircraft-fixed home position and as long as this is within the pilot's FOV, the VCI behaves like in the normal *Aircraft-Fixed* mode. However, as soon as the pilot looks farther away from the aircraft-fixed VCI, the system transitions to its second state: the *Head-Fixed* sub-mode. This implies that the VCI is then

(a) Mode/Sub-Mode: Aircraft-Fixed,
Position: HDD,
Study I conditions: 1, 2, 5, 7, 8,
Situation: final approach, target wind turbine ahead.



(b) Mode/Sub-Mode: Aircraft-Fixed,
Position: Free,
Study I conditions: 4, 10,
Situation: sideways hover, pilot looking to the desired hover position at the right.



(c) Mode/Sub-Mode: Clipped,
Position: 4-Way,
Study I conditions: 5, 6,
Situation: sideways hover, pilot looking to the wind turbine at the right.

(d) Mode/Sub-Mode: Head-Fixed,
Position: Below,
Study I cond.: 7–14 (partly w/o HU-PFD),
Situation: hover phase, pilot looking to the wind turbine at the right.

Figure 5.8 – Selected VCI positioning options during different phases of an approach and hover maneuver at an offshore wind turbine. The red symbol illustrates the pilot's head direction in the head-coupled conditions — it is not part of the symbology (own illustrations [73]).

coupled to the pilot's head like in the pure *Head-Fixed* mode. For transition option 2 (study II), this switchover happens when a new flight phase starts, for instance at the transition from approach to hover. In summary, the *Mixed* mode appears like Fig. 5.8a in the first sub-mode (here in HDD position) and like Fig. 5.8d in the other sub-mode (here with head-up PFD).

Aircraft-Related The *Aircraft-Related* variant is also a combination of the conventional *Aircraft-Fixed* mode with a head-coupled state. Similar to *Mixed*, if the pilot turns the head and the aircraft-fixed instrument leaves the FOV, the VCI will be re-positioned to a head-referenced position. In this case, however, it is not always the same head-fixed position; the VCI is placed on the side of the FOV which is closest to the home position. Fig. 5.8c shows one exemplary state: The pilot has turned the head to the right and the aircraft-fixed instrument left the FOV on the left. Thus, the system transitioned to the *Clipped* sub-mode and the VCI now appears in the left area of the pilot's FOV. This process is reversed when the aircraft-fixed VCI comes back into view. The position is called "4 Way" since the VCI can reside in four locations dependent on if the VCI's home position is left, right, above, or below the current FOV.

5.1.4 Obstacle Awareness Symbology for the VCI

As mentioned above, the presented VCI approach will now be used to integrate an OAWD for low-speed maneuvers in confined areas. Inspired by the display formats presented by Airbus Helicopters and Leonardo (Sec. 2.2.6.1), Ebrecht [53, 54] implemented a VCI-adapted obstacle awareness and warning display (VCI-OAWD). It was specifically customized for the usage as a VCI on a see-through display. Further, it was adapted to the monochrome green color of the JedEye, DLR's flight-certified HMD. This thesis uses Ebrecht's OAWD implementation as an exemplary VCI symbology to evaluate the developed VCI concept and assess the various positioning options introduced above.

Figure 5.9 shows the two pages of Ebrecht's VCI-OAWD. The approach page is similar to a conventional navigation display in rose mode. It shows the approach route, surrounding objects, and various supplemental information like the current wind conditions et cetera. The hover page is activated when the helicopter passes a certain distance to the desired hover position. It provides an orthogonal 360° top view of the near field including the desired hover

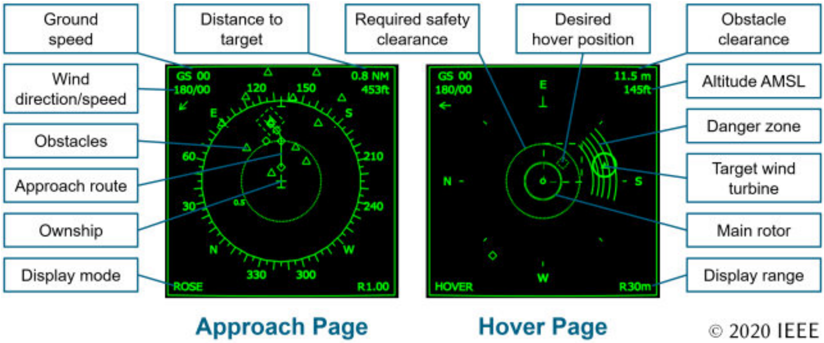


Figure 5.9 – The two pages of Ebrecht's obstacle awareness symbology for the VCI. The display switches from the approach to the hover page when passing a certain distance to the desired hover position. The black background corresponds to transparent areas in the see-through HMD [70, 72].

position and nearby obstacles. To improve the pilot's distance estimation, it renders two circles indicating the main rotor size and the required safety clearance. Similar to Airbus' RSAS [332], the area around the ownship is divided into sectors which are highlighted if an obstacle is detected within that zone.

5.1.5 Required Data Sources

A VCI itself requires only a head-tracked HMD. If its roll orientation should be aligned with the world-fixed horizon, as described in Sec. 5.1.2.3, the algorithm additionally needs the aircraft attitude. For its display content, the VCI requires the same data inputs that a corresponding PMD takes. For the presented use case, this would be a near-field obstacle sensor system. More information about the avionics integration and a possible path to certification is given in Sec. 5.4.2

5.2 Evaluation Method

Two simulator studies were conducted to assess the VCI implementation. This section describes the methods of both experiments. As discussed above, the VCI approach can be used on both AR- and VR-HMDs, where the former may act as a near-term solution and intermediate step towards the long-term goal of a completely virtual cockpit. Here, study I was conducted in a VR configuration while study II applied an AR setup with the flight-certified JedEye HMD. The VCIs tested in the VR experiment were designed such that the findings can be easily transferred to an AR setup: The VCIs were monochrome green with transparent background and the pilots sat inside a virtual mockup of a conventional cockpit, as seen in Fig. 5.8.

5.2.1 Research Questions

The overall research goal for both evaluation studies was to get initial feedback on how pilots rate the novel VCI approach in general. Further, it was examined if this specific VCI showing an OAWD is useful for the tested confined area operations. Section 2.4 described that 2-D orthographic top-view displays are very common on flight decks, for instance because they provide a good overview and allow for better distance estimation than the natural 3-D egocentric perspective. However, this research has to answer if the integration of such a display as transparent VCI into the natural view helps the pilots because of its increased availability or if the overlay of these two non-conformal domains causes unwanted confusion.

Study I VCIs can be positioned in many ways (see Sec. 5.1.3). Thus, the focus of the first evaluation was the investigation of the effects of the VCI position and the selection of the most promising positioning options. Further, different VCI sizes and the interplay with the head-up PFD were tested.

Study II The condensed number of feasible VCI variants and all other findings from study I formed the basis for the second evaluation. This time, the pre-selected variants were assessed in an advanced simulation environment with DLR's flight-certified JedEye HMD. This was to confirm that the positive appraisal from the pre-study holds true when a see-through HMD is used.

5.2.2 Participants

Study I Eleven subjects (1 female, 10 male) with a mean age of 38 (between 26 and 61) took part in the simulator study. All participants had experience with helicopter-flying, either in the simulator or in real flight. Three held a helicopter license (2 airline transport pilot licenses (ATPL), 1 commercial pilot license (CPL)), five held a fixed-wing license. The actual flight hours (without simulator hours) ranged from 0 to 6400 (mean: 1248 h). Seven subjects had a mean experience of 56 h with HMDs. All participants had normal or corrected to normal vision.

Study II Seven male helicopter pilots with an average age of 46 (range from 38 to 62) participated in the experiment. They had a mean flight experience of 1985 h. One held a private pilot license (PPL), four a CPL, and two an ATPL. Five pilots reported prior HMD experience (mean: 108 h). Three of them already participated in the first VCI study. All participants had normal or corrected to normal vision.

5.2.3 Apparatus

Both studies used the specially developed XR-Sim environment, however in a very different configuration. The simulator setups are described here in short; details can be found in Chapter 4.

Study I The first study used the XR-Sim in standalone configuration II: “AR-emulation through VR” (see Tab. 4.3). As shown in Fig. 5.10a, the participants wore the Oculus Rift CV 1, which created a fully immersive virtual environment. The virtual world comprised the cockpit, the out-the-window view, and the superimposed AR-symbology (see Fig. 5.8).

The flight mechanics were simulated by DLR’s custom-made EC135 flight model introduced in Sec. 4.2.2. The included FCS provides several upper command and hold modes, which simplifies the helicopter control task. For these trials, the following modes were active: *attitude command, attitude hold* for both cyclic axes, *vertical velocity command, height hold* for the collective, and *rate command, direction hold* for the pedals. This allowed the participants to directly command a pitch or roll attitude, while a neutral cyclic stick position made the helicopter return to trimmed attitude. Sink or climb rates were directly controlled via the collective. With the collective in neutral position, the FCS held the altitude regardless of any cyclic stick inputs. Via the pedals, the pilots could steer the yaw rate.

(a) Study I — Fully virtual setup with a pilot wearing the Oculus Rift VR goggles.

(b) Study II — Pilot wearing the JedEye see-through HMD in the GECO simulator.

Figure 5.10 – Experimental setup of the two VCI simulator studies [54, 73].

Study II For the follow-up experiment, the XR-Sim environment was configured for the evaluation of state-of-the-art see-through systems (mode IV). As introduced in Sec. 4.3, this setup employs an AR-HMD inside a conventional cockpit simulator. Here, the JedEye helmet in DLR's GECO was used. Figure 5.10b illustrates the whole setup with the HMD, the PMD, and the offshore wind farm presented on the projection system. The flight simulation was provided by X-Plane using a customized Eurocopter EC135 model without upper modes, as described in Sec. 4.2.2.

As visible in the picture, the cockpit shell of the GECO replicates an Airbus A350, which leads to a restricted out-the-window view compared to most helicopters. Despite this limitation, the collimated outside vision and the JedEye provide a very realistic HMD experience, which makes this simulator a good choice for this experiment and the study a valuable step before the flight test with DLR's research helicopter.

5.2.4 Task

The pilots' task was similar in both experiments. It was derived from the maneuver that helicopter pilots perform to hoist persons to the lower access platform of offshore wind turbines (see Sec. 3.4.2 and Fig. 3.19 for details). The participants had to conduct an approach to the wind turbine and perform a simulated hoist maneuver at its lower access point. The runs were started in-flight, approximately 0.8 NM from the target position. The pilots had to fly a left turn towards the wind turbine and into the wind. As depicted in Fig. 3.19a, the final approach was a straight descent towards a point left of the wind turbine. From there, the final segment was a horizontal transition to the desired hover position. At that point, the wind turbine tower was located at the pilot's 3 o'clock position with half a rotor diameter clearance between the main rotor tips and the tower. As soon as they reached this position, they had to acknowledge "on position" by pressing the trigger button on the cyclic. From then on, the task was to hold this position as precisely as possible for 60 seconds.

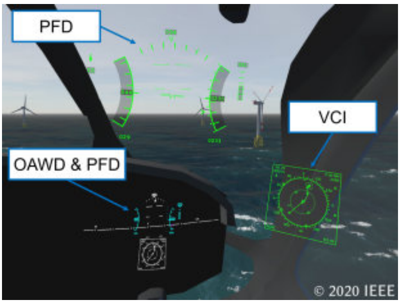
A difference between both studies were the wind conditions. In the first evaluation, gusts of varying strength and direction were simulated. This complicated the precise position holding during the hover maneuver. The applied upper control modes simplified the flying task itself but the uncompensated influence of the fast-changing wind conditions required the pilots to continuously monitor their drift and act accordingly. In contrast, the second experiment had no gusty wind but two different steady wind conditions as independent variable (see experimental design below).

5.2.5 Experimental Design & Tested VCI Variants

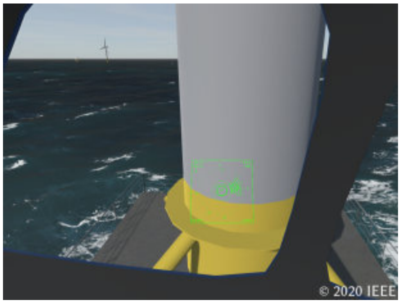
Both studies were designed as a within-subject experiment.

Study I The test matrix of the first study is depicted in Tab. 5.1a. It comprised 14 test conditions and three independent variables. First, different VCI positioning modes and their various connected positions — as introduced in Sec. 5.1.3 and Fig. 5.7 — were tested. Second, the size of the VCI was varied for selected positioning modes, from barely to clearly readable. Third, the standard aircraft-referenced tapes of the head-up PFD were occasionally altered to a head-fixed mode, where these elements stayed in the pilots' FOV regardless of their head rotations. Figure 5.8d depicts this head-fixed tape mode. In the aircraft-fixed counterpart, the PFD tapes would remain attached to the helicopter's forward axis as in Fig. 5.8a. In all conditions, the PMDs were switched off and the head-up PFD and the VCI were the only flight guidance symbology available.

Study II The follow-up study involved two independent variables: 1) display type and 2) wind condition. The wind variable had two wind strength levels: 10 knots and 25 knots, both from 90° (corresponding to head-wind during hover). The display variable comprised three conditions, which were characterized by the type of VCI tested on the JedEye helmet: 1) no VCI, 2) mixed VCI, and 3) head-fixed VCI. As shown in Tab. 5.1b, the HMD additionally displayed an aircraft-fixed head-up PFD in all conditions. Also, the PMD showed the same information throughout the whole experiment: a colored, head-down version of the developed symbol set including the OAWD and the PFD (see Figs. 5.10b and 5.11a). The first two test conditions represented the experiment baseline with the OAWD only visible on the PMD. Thus, this test condition is called *PMD-OAWD*. All other conditions included the VCI-OAWD



(a) An aircraft-fixed VCI during the approach phase: The VCI is positioned right of the instrument panel. The image also shows the head-up PFD and the symbology displayed on the PMD (PFD & OAWD). This display setup corresponds to the aircraft-fixed state of display variant *VCI-Mixed* in study II (ID: 5, 6).



(b) A head-fixed VCI during hover: The VCI follows the pilot's head movements and remains within the field of view. Here, the pilot looks to the right towards the wind turbine. This corresponds to the condition *VCI-HeadFixed* and the head-fixed state of *VCI-Mixed* in study II (ID: 3–6).

Figure 5.11 – The display conditions tested in study II during different phases of the task (illustrations generated in VR setup) [70, 72].

Table 5.1 – The test matrices of the two VCI experiments. Each table line corresponds to one test condition. The different colors are chosen to match the coloring of the results plots in the following section. © 2019 IEEE [70, 72, 73].

(a) Study I — Independent variables were the VCI positioning mode incl. VCI positions (see Figs. 5.7 and 5.8), the VCI size, and the tape mode of the head-up PFD.

ID	VCI Positioning			VCI Size	Head-Up PFD
	Mode	Position Aircraft-Frame	Position Head-Frame	[deg]	Tape Mode
1	Aircraft-Fixed	HDD	—	14	Head-Fixed
2	Aircraft-Fixed	HDD	—	14	Aircraft-Fixed
3	Aircraft-Fixed	HUD	—	14	Aircraft-Fixed
4	Aircraft-Fixed	free	—	14	Aircraft-Fixed
5	Aircraft-Related [a]	HDD	4-Way	14	Aircraft-Fixed
6	Aircraft-Related [a]	HUD	4-Way	14	Aircraft-Fixed
7	Mixed [a]	HDD	below	14	Aircraft-Fixed
8	Mixed [a]	HDD	below	14 & 10	Aircraft-Fixed
9	Mixed [a]	HUD	below	14	Aircraft-Fixed
10	Mixed [a]	free	below	14	Aircraft-Fixed
11	Head-Fixed	—	below	14	Head-Fixed
12	Head-Fixed	—	below	14	Aircraft-Fixed
13	Head-Fixed	—	below	12	Head-Fixed
14	Head-Fixed	—	below	12	Aircraft-Fixed

[a] VCI position changes from the aircraft- to the head-frame based on *pilot's line of sight*.

(b) Study II — Independent variables were the display condition and the wind condition. The former includes HMD symbology, VCI positioning, and PMD symbology.

ID	Display Condition					Wind Cond.
	HMD Symbology	VCI Positioning Mode	Position Aircraft-Frame	Position Head-Frame	PMD Symb.	Wind Speed [knots]
1	PFD	—	—	—	OAWD & PFD	10
2	PFD	—	—	—	OAWD & PFD	25
5	PFD + VCI	Mixed [b]	beside panel	below	OAWD & PFD	10
6	PFD + VCI	Mixed [b]	beside panel	below	OAWD & PFD	25
3	PFD + VCI	Head-Fixed	—	below	OAWD & PFD	10
4	PFD + VCI	Head-Fixed	—	below	OAWD & PFD	25

[b] VCI position changes from the aircraft- to the head-fixed frame based on the *flight phase*.

in two different positioning modes. The first, *VCI-HeadFixed*, was identical to the display tested in the first study (see Fig. 5.11b). The second, *VCI-Mixed*, was a "mixed" variant, where the position of the VCI changed during the flight. Here, it changed from an aircraft-fixed position right of the instrument panel (see Fig. 5.11a) to a head-fixed position similar to *VCI-HeadFixed* (see Fig. 5.11b). In contrast to the first study, however, the position changes were not triggered by the pilot's viewing direction. Instead, it only changed once at the transition between the approach and the hover phase. This means that during the 60 s hover maneuver, the symbology of *VCI-Mixed* and *VCI-HeadFixed* was identical. Finally, it should be noted that no visual depth of the VCI and other HMD symbology was created (no stereo).

5.2.6 Procedure

At the beginning of both experiments, the pilots received a comprehensive introduction and briefing. Thereafter, they conducted several training flights to get accustomed to the simulator, the tasks, and the different symbol sets. The training duration was adapted to the individual needs of each pilot such that everyone could perform the task at a sufficient level when the testing phase was started. After a break — during which the participants filled out a biographical survey — the testing phase started.

Study I The subjects ran through the 14 test conditions in counterbalanced order with a break after about half of the scenarios. They completed a post-flight questionnaire after each run and a debriefing form at the end of the experiment. The total study duration ranged from 2.5 h to 4 h.

Study II The testing phase was split into two blocks. In one block the participants flew the six hover maneuvers described above (3 displays × 2 wind conditions). The other block comprised eight landings on an offshore platform. The evaluation of this landing part is not part of this thesis. It can be found in [54]. The order of the task blocks as well as of the display and wind conditions was counterbalanced between the participants. A break was scheduled between the two blocks. The subjects completed several tailor-made questionnaires: a post-flight questionnaire including the 3-D Situation Awareness Rating Technique (3-D SART) [302], post-block surveys containing specific questions for the two major parts of the study, and a final debriefing questionnaire. In total, the experiment took about 4 h.

5.3 Evaluation Results

Table 5.2 gives an overview of the dependent measures presented in this section. The overall appraisal of the VCI and the selection of the preferred positioning mode is based on several questionnaires and pilot comments collected during the experiment. Objective measurements were used to investigate the effects of the display conditions on the flight performance and the pilot's head-up, eyes-out time. The recorded aircraft state, flight path, and head-tracking data as well as the questionnaire answers were preprocessed and analyzed with MATLAB [182]. More than the listed parameters were evaluated but only the most important findings were selected for the thesis.

Table 5.2 – Overview of the dependent measures used in study I & II.

Research Question	Indicators	Measures*
Overall VCI Appraisal	Comparison VCI — PMD VCI size, readability, clutter Integration with other symb.	PFQ, PBQ, DBQ PFQ, PBQ, DBQ PFQ, DBQ
Preferred Positioning Mode	Pre-selection study I Revised versions study II	PFQ, DBQ PBQ, 3-D SART
Flight Performance	Hover accuracy	Flight path Covered track
Head-Up, Eyes-Out Time	Head motion	Head rotation

* PFQ = post-flight questionnaire, PBQ = post-block questionnaire, DBQ = debriefing questionnaire, 3-D SART = three-dimensional situation awareness rating technique [302].

5.3.1 Overall Appraisal of the VCI

Overall, the VCI concept was received very positively. In the second study, all pilots except one stated that their general impression of the VCI concept is "good" or "very good" (see Fig. 5.12). Correspondingly, many pilots assessed the value of the VCI as "(very) helpful" during both approach and hover. According to Fig. 5.12, the VCI seemed to be more helpful for the hover phase; in general lower but still positive ratings were received for the approach.

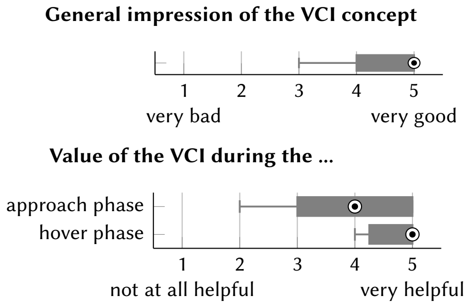


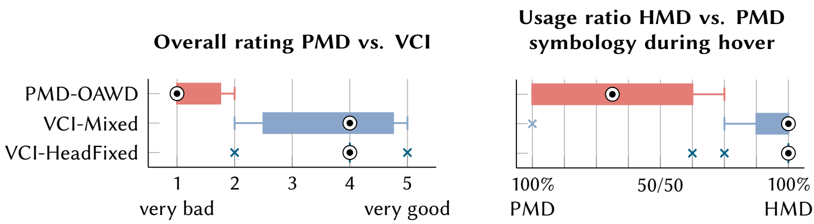
Figure 5.12 – Rating of the virtual cockpit instrument.[4] © 2020 IEEE [54, 70, 72].

5.3.1.1 Virtual Cockpit Instrument versus Panel-Mounted Display

A remarkable result is that all pilots preferred to have the hover symbology as a VCI instead of having it on a conventional PMD. This also matches the subjects' overall conclusion on the three display conditions they tested with the JedEye. Figure 5.13a shows that both variants containing the VCI were rated significantly better than the baseline *PMD-OAWD* condition, where the OAWD was displayed only on the PMD and the head-up symbology comprised only a PFD. The median overall rating for both VCI conditions was "good". However, while almost all pilots agree on their rating of *VCI-HeadFixed*, the results of *VCI-Mixed* show noticeable disagreement between the participants. The good VCI ratings go in line with all participants agreeing to the statement that "in the future, more information that is currently presented on conventional PMDs should be displayed on the HMD."

Figure 5.13b depicts the pilots' estimation of how much they used the PMD compared to the HMD symbology. Obviously, since the baseline condition showed only a head-up PFD without further hover/obstacle information on the HMD, the participants looked down to the PMD very often. The median head-down usage ratio was approximately 70 %. On the contrary, the VCI drastically decreased the head-down time to almost zero.

[4] Boxplots show median (dot/circle), 25th and 75th percentiles (filled rectangle), and outliers (x markers) with whisker length 1.5 interquartile range.



(a) Overall rating of the presented display sets.

(b) Usage ratio head-up vs. head-down symbology.

Figure 5.13 – Comparison of the PMD-based vs. the VCI-based OAWD in study II with the JedEye HMD.[4] © 2020 IEEE [70, 72].

5.3.1.2 VCI Size, Readability, and Clutter

Three different VCI sizes were compared in the VR-based study I. All subjects agreed that $14° \times 14°$ was a proper size for the VCI. The smaller variants (test conditions 8, 13, 14) were perceived as too small. Of course, the selection of a proper size depends largely on the VCI contents and the resolution of the HMD. On the Oculus Rift CV 1, this size corresponds to a display area of approximately 194×194 pixels [163]. On the JedEye with its higher angular resolution, the VCI size was reduced to approximately $10° \times 10°$ or 270×270 pixels. The majority of pilots in this second study indicated that this was a good size. A few would prefer to slightly increase the VCI.

The virtual instruments are see-through displays where the symbology is superimposed onto the reality. Therefore, the readability of the VCI is not only a matter of size and resolution but also of the instrument's background. Depending on the VCI positioning mode, the background can be uniform and constant or heterogeneous and ever-changing.

The first study compared several positioning options. It found that the reality behind the VCI had a strong negative impact on the readability when the VCI was located at the HUD position. The subjects explained that they had major problems reading the symbology since the horizon crossed the VCI in the background. The differences between the dark ocean in the lower half and the bright sky in the upper half of the display caused strong contrast issues. On the contrary, the VCI projected onto the dark instrument panel

(*AircraftFixed-HDD*) performed best. The most important finding of the first study was that all head-coupled variants caused no or only weak readability issues — despite the often non-uniform and continually changing instrument background.

A major question of the second experiment was whether the good readability of the head-coupled variants on the VR goggles could be confirmed with an actual see-through HMD. As illustrated in Fig. 5.14, this can be answered with yes: The participants acknowledged that the underlying reality had no negative influence on the readability of the VCI.

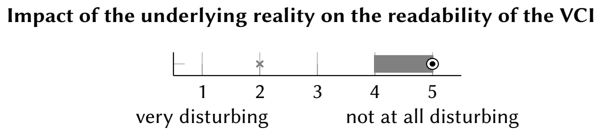


Figure 5.14 – Readability of the VCI on the JedEye.[4] © 2020 IEEE [54, 70, 72].

The pilots are not only interested in reading the VCI but also want to monitor the real world. Thus, it is not enough to guarantee that the underlying reality does not degrade the readability of the VCI. Vice versa, one also has to ensure that the VCI being overlaid onto the reality does not disturb the pilots' out-the-window view. The participants reported that the VCIs did not clutter the natural vision in most conditions. Only the VCI positioned in flight direction above the panel (*AircraftFixed-HUD*) masked too much of the central, forward FOV.

In summary, the results of both studies show that the VCI size and position should be chosen carefully because this may have strong effects on readability and clutter. The setups for study II (*Mixed*, *Head-Fixed*) were found to be reasonable choices in that matter.

5.3.1.3 Integration with State-of-the-Art Head-Up Symbology

Usually, an HMD is not used exclusively to display a VCI. It typically shows other symbol sets like a head-up version of a PFD or various kinds of conformal

[4] Boxplots show median (dot/circle), 25th and 75th percentiles (filled rectangle), and outliers (x markers) with whisker length 1.5 interquartile range.

flight guidance symbology. Therefore, the experiments also checked how these different types of symbology can be integrated with each other.

Head-Up PFD The first study tested the VCI together with a head-up PFD. Thereby, two modes of the PFD's speed and altitude tapes were tested. The standard aircraft-fixed mode — where the PFD tapes remained attached to the aircraft's forward axis (Fig. 5.8a) — was favored by 9 out of 11 participants. The head-coupled PFD tapes, which always stayed in the pilots' FOV next to the head-fixed VCI (Fig. 5.8d), were disregarded by many pilots. The main reason for this is that the speed and altitude information on the tapes is primarily needed during the approach phase when the pilot's view is mostly oriented in flight direction. During the hover phase, the pilot is mainly focused on outside visual cues and rarely needs the information given by the PFD tapes. Having the tapes always moving with the head clutters the important out-the-window view during this maneuver. Also, several subjects noted that the head-fixed PFD tapes were rather big compared to the VCI. These issues explain why the majority of pilots preferred the tapes being fixed to the aircraft's forward axis, where they represent a single entity with other PFD elements like the artificial horizon.

Conformal Symbology As detailed in Sec. 2.3, conformal and scene-linked symbology is a proven way to present information on an HMD. Thus, Ebrecht et al. [54] tested the integration of the VCI-OAWD with DLR's conformal landing symbology. This work shows that pilots benefit from the simultaneous inclusion of both symbol sets even though the combined setup seems quite complex at first.

5.3.2 Comparison of the Positioning Options

A major goal of study I was the assessment and pre-selection of the various VCI positioning modes introduced in Sec. 5.1.3. The findings were then used to improve the symbology and to further evaluate the most promising variants in study II. This process is presented in the following.

5.3.2.1 Pre-Selection in Study I

Overall Rating Figure 5.15 shows the overall rating of the VCI modes given by the pilots via the debriefing questionnaire of study I. *Mixed-HDD-Below* and *HeadFixed-Below* appear to be the preferred variants, closely followed by the conventional *AircraftFixed-HDD* mode and *Mixed-Free-Below*. All options comprising the aircraft-fixed *HUD* position were rated inferior to their *HDD* and *Free* counterparts. The poor rating is mainly explained by readability and clutter issues (see Sec. 5.3.1.2).

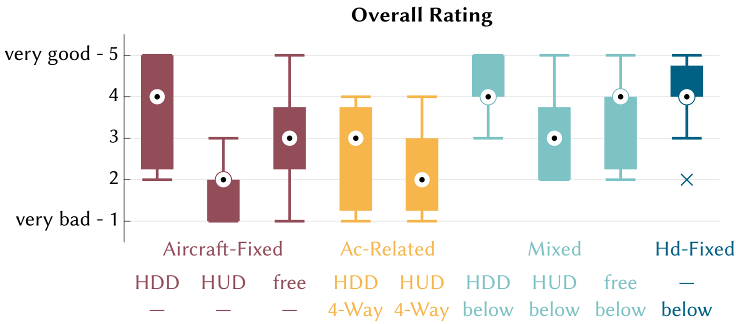


Figure 5.15 – Overall rating of the VCI modes (introduced in Figs. 5.7 and 5.8).[4] © 2019 IEEE [54, 73].

VCI Positioning After each of the 14 flights, the participants were asked to assess how satisfied they were with the previously tested VCI position and — if applicable — the position changes between aircraft- and head-coupled sub-mode (*Aircraft-Related* and *Mixed* only). Fig. 5.16 indicates that *HeadFixed-Below* was the favored position. The participants explained that the head-fixed VCI offers a great advantage during the hover maneuver: They can monitor their exact position on the VCI while looking out the window toward the obstacle (see Fig. 5.11b). This is also the reason why the combination of this head-fixed mode with the aircraft-fixed head-down position (*Mixed-HDD-Below*) received rather positive feedback. It has the additional benefit of a non-moving, non-distracting head-down instrument during the approach when the pilots look in direction of flight.

[4] Boxplots show median (dot/circle), 25th and 75th percentiles (filled rectangle), and outliers (x markers) with whisker length 1.5 interquartile range.

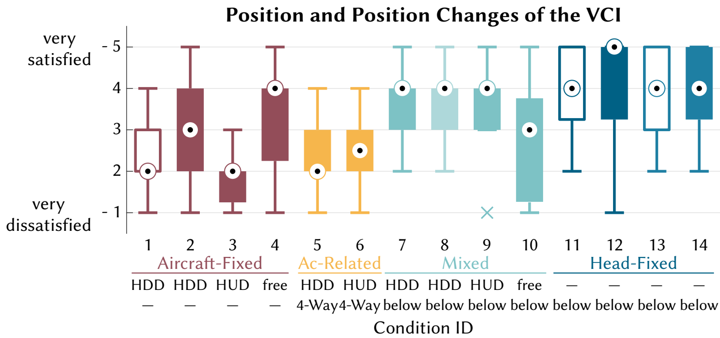


Figure 5.16 – Pilots' satisfaction with the VCI position and — if applicable — with the position changes between the sub-modes. Outline-only boxes represent conditions with head-fixed PFD tapes, light-colored boxes represent conditions with smaller VCI size (see Tab. 5.1a for condition details).[4] © 2019 IEEE [73].

AircraftFixed-Free received a positive median rating of 4. However, the interquartile range indicates that a number of subjects were not satisfied with this mode. They reviewed that during the hover the VCI was not positioned far enough to the right so that they still had to turn their heads or eyes to switch between turbine tower and VCI. Also, during the approach, the display position was criticized as too far right of the aircraft's forward axis. Nevertheless, the *AircraftFixed-Free* position was very convenient in the transition phase to the hover position (Fig. 3.19a: level segment between point 1 and 2). During that, the pilots looked outside and moved slowly towards the wind turbine. The VCI was positioned exactly in that area such that the pilots could use both the out-the-window view and the symbology without turning their heads. The VCI positions of the other *Aircraft-Fixed* variants were rated lower than the *AircraftFixed-Free* version.

Mixed-Free-Below and its position switches between the aircraft-fixed and the head-fixed sub-mode caused a wide range of ratings from "very satisfied" to "very dissatisfied". Several pilots pointed out that a smoother transition between both positions is required. Both *Aircraft-Related* conditions received low ratings because of their VCI positions when in the head-coupled *Clipped* mode. For many pilots, the instruments located near the FOV borders were inconvenient to read since rather large eye rotations were required. These results confirm the importance of the optimal eye rotation zones given by Tilley [313] (see Fig. 5.5).

Availability & Information Retrieval Effort As expected, the pilots confirmed that they were more satisfied with the availability of the instrument in modes comprising head-fixed symbology (*Mixed*, *Head-Fixed*). As a consequence, the effort to retrieve required information was in general higher with the *Aircraft-Related* and the *Aircraft-Fixed* variants. In the LOS-coupled modes, however, the pilots could orientate themselves towards the wind turbine and easily switch their sight between outside vision and VCI just by small eye movements. They could even perceive the relative obstacle motion via their peripheral vision while focusing on the VCI.

Spatial Awareness According to Fig. 5.17, this increased availability appears to positively affect the pilots' perceived spatial awareness. All conditions comprising a head-coupled VCI were reported to create high awareness of the obstacle position.

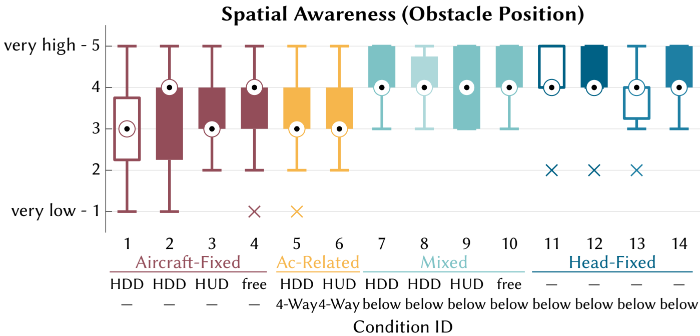


Figure 5.17 – Pilots' perception of their own spatial awareness. Outline-only boxes represent conditions with head-fixed PFD tapes, light-colored boxes represent conditions with smaller VCI size (see Tab. 5.1a for condition details).[4] © 2019 IEEE [73].

Attention Fixation Finally, the pilots were asked if they encountered situations in which they focused so much on the VCI that they missed other

[4] Boxplots show median (dot/circle), 25th and 75th percentiles (filled rectangle), and outliers (x markers) with whisker length 1.5 interquartile range.

relevant information. As depicted in Fig. 5.18, the subjects reflected that this occurred less frequently with the *Head-Fixed* and the *Mixed* mode compared to *Aircraft-Fixed* and *-Related*. This supports the hypothesis that a head-fixed VCI allows the pilot to look at the instrument while having, for instance, the peripheral perception of the movement relative to the obstacle. Nevertheless, numerous studies on head-up, see-through displays demonstrated that attention fixation can be a major problem of such augmented reality symbology [e.g. 173, 248]. It is also disputable how good pilots can estimate their own attention allocation and the usage ratio between VCI and out-the-window view. Thus, further investigations should use a more objective measurement technique like the subject's reaction to unexpected events in the out-the-window view.

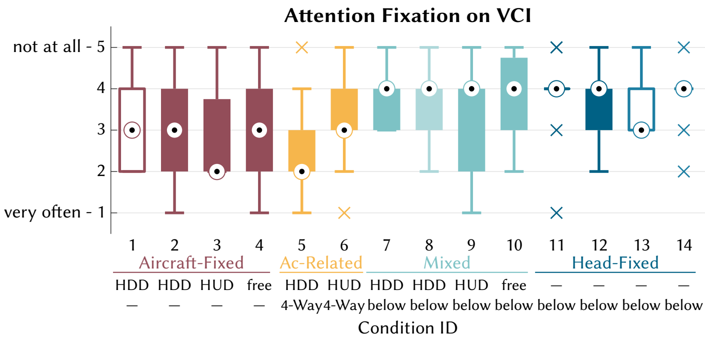


Figure 5.18 – Pilots' experience of situations in which they focused so much on the VCI that they missed other relevant information (attention fixation). Outline-only boxes represent conditions with head-fixed PFD tapes, light-colored boxes represent conditions with smaller VCI size (see Tab. 5.1a for condition details).[4] © 2019 IEEE [73].

5.3.2.2 Revised Versions in Study II

In summary, the conditions *HeadFixed-Below* and *Mixed-HDD/Free-Below* were the preferred variants of study I, closely followed by the more conventional *AircraftFixed-HDD* mode. The follow-up study built on these results by taking a closer look at improved *Mixed* and *Head-Fixed* modes and comparing these with an aircraft-fixed, head-down baseline, in the form of a PMD.

The *VCI-HeadFixed* condition on the JedEye HMD was similar to its counterpart in study I. The *VCI-Mixed* mode in study II was improved based on the pilots' feedback from study I. As explained in Sec. 5.2.5, the sub-mode change was now triggered based on the flight phase instead of the pilot's head motion. This implies that the VCI was located at an aircraft-fixed position beside the instrument panel during the approach phase. As soon as the pilot transitioned to the hover phase, the VCI switched to a head-fixed position similar to *VCI-HeadFixed*. When asked about their preferred positioning mode, two pilots chose *VCI-HeadFixed*, three favored *VCI-Mixed*, and the remaining two stated that both are equal.

To further assess the *Mixed* mode, the participants were queried on the helpfulness of the different VCI behavior in the two phases of the flight. Figure 5.19 confirms that this was seen as helpful. Also, the selected VCI position for the approach phase — right of the instrument panel (see Fig. 5.11a) — was satisfying for the majority of the pilots.

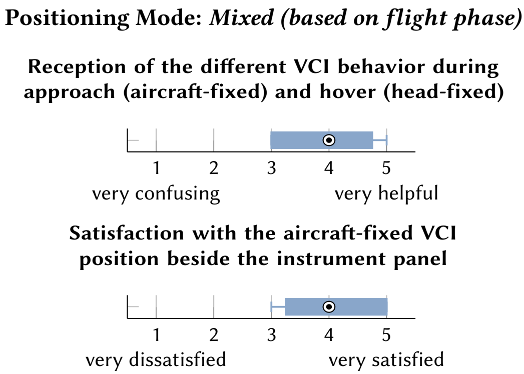


Figure 5.19 – Rating of the VCI positioning mode *Mixed (based on flight phase)* in study II.[4] © 2020 IEEE [70, 72].

Finally, Fig. 5.20 shows the results of the 3-D SART questionnaire [302]. It did not reveal significant differences between the three test conditions.

[4] Boxplots show median (dot/circle), 25th and 75th percentiles (filled rectangle), and outliers (x markers) with whisker length 1.5 interquartile range.

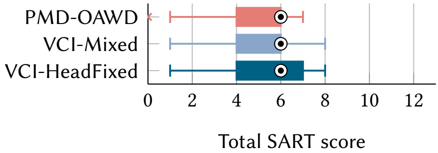


Figure 5.20 – Results of the 3-D SART [302] in study II.[4] © 2020 IEEE [70].

5.3.3 Flight Performance — Hover Accuracy

The pilots' task during the hover maneuver was to hold the target position as precisely as possible for 60 s. The achieved positional accuracy is illustrated for both studies by means of two graphs respectively: First, the horizontal flight paths during the hover via a top view were checked. Second, the length of the track that each pilot covered within these 60 s was computed. The corresponding plots are given in Figs. 5.21 and 5.22.

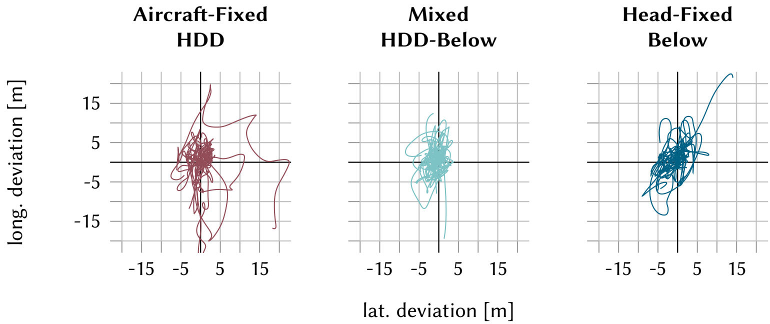
5.3.3.1 Study I — VR-Goggles with Normal Out-the-Window View

Overall, the flight paths of the three pre-selected display conditions in study I appear to be alike. The top views in Fig. 5.21a show good and similar positional accuracy for all variants. Also, the boxplots of the covered track give a uniform picture. However, with *AircraftFixed-HDD* the participants seem to have lost control in two runs. This led to significantly longer covered tracks, large deviations, and even rotor strikes for these flights.

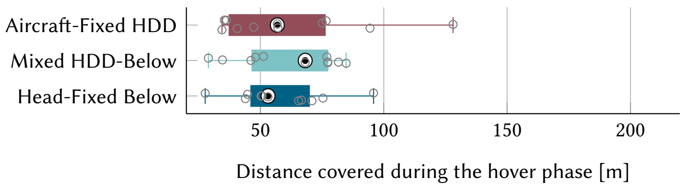
5.3.3.2 Study II — JedEye with Restricted Out-the-Window View

Figure 5.22 shows larger deviations for *PMD-OAWD* compared to both VCI variants in the second study with the restricted out-the-window view of the GECO simulator. The pilots' difficulties in holding the desired hover position are also reflected in the track covered during the hover phase. Figure 5.22b reveals that *PMD-OAWD* caused longer tracks for several flights.

The positional accuracy observed in the second study was overall lower in the GECO than with the fully virtual setup. The top views of all variants indicate



(a) Top view of the flight paths.

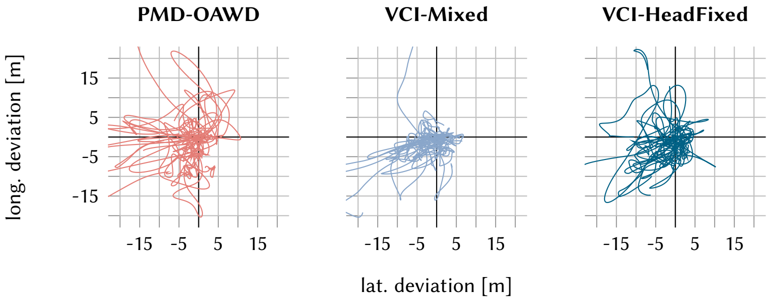


(b) Covered track of each flight.[5]

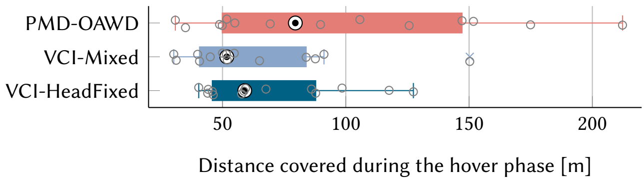
Figure 5.21 – Positional accuracy during the 60 s hover phase of the VR-based study I (selected display variants). © 2020 IEEE [70, 72].

that the flight paths covered a much wider area. Also, the predominant deviation direction seems to be left behind the desired hover position (in the third quadrant of the graph). The reason for that phenomenon is presumably that in this position the wind turbine tower was easier to observe from the cockpit: The obstacle then appears not at 90° to the right but rather at around 45°.

[5] Boxplots show median (black dot/circle), 25th and 75th percentiles (filled rectangle), and outliers (x markers) with whisker length 1.5 interquartile range. Raw values are illustrated by gray circles.



(a) Top view of the flight paths.



(b) Covered track.[5]

Figure 5.22 – Positional accuracy during the 60 s hover phase of the JedEye study II. © 2020 IEEE [70, 72].

5.3.4 Head Motion

The idea behind a head-fixed VCI-OAWD was to enable the pilots to look out the window (and at the obstacles) more often than with a conventional PMD-based OAWD. The histograms in Fig. 5.23 indicate that the result is as intended. To see the wind turbine tower during the hover, the participants had to turn their head about 50° to the right. The distribution of the head yaw rotations shows that — in all three display conditions — the pilots had two distinct areas of interest: in forward direction (0°) and in rightward direction (around 50°). However, the time spent in these areas varies significantly between the VCI positioning modes.

With *AircraftFixed-HDD*, the pilots' viewing direction was predominantly oriented straight ahead and rarely to the right where the wind turbine tower was located. This was expected since the VCI was located in forward direction,

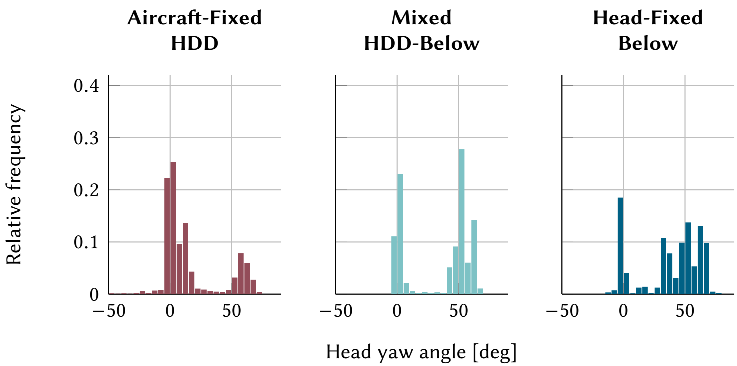


Figure 5.23 – Distribution of the pilots' head yaw rotation during the hover maneuver. Positive values correspond to viewing directions to the right where the wind turbine was located. © 2020 IEEE [70, 72].

superimposed onto the instrument panel. Nevertheless, the pilots did not solely use the symbology but also — at times — looked to the obstacle on the right. In contrast, the two variants with the head-coupled VCI prompted the participants to make use of the VCI being always in sight: They looked much more to the right, where they could see both VCI and obstacle (see Fig. 5.11b).

Interestingly, with *Mixed-HDD-Below* the subjects hardly ever looked in direction between the two narrow areas of interest, whereas for *HeadFixed-Below* the gap between the peaks is less prominent and the right area of interest is considerably wider. This can be explained by the mode switching mechanism of the *Mixed* mode in study I. The VCI switched from its aircraft-fixed head-down position to its head-fixed position if the pilot looked more than 23° to the side. This caused the VCI to jump whenever the pilot's head direction crossed this limit. Thus, the subjects avoided this transition area. This behavior was changed for the *Mixed* mode in study II: The position changes were not triggered by the head motion anymore but coupled to the flight phase.

In the second study, the limited simulation environment prevented the observation of this head motion behavior. The A350-like cockpit strongly restricted the pilots' out-the-window view. Further, the outside vision projection system could not supply sufficient side-view. Therefore, the head-motion patterns were not as pronounced as during the VR study, which provided a much more realistic simulation of the pilot's view from a real helicopter cockpit.

5.4 Discussion

Overall, the evaluation studies explicitly confirm the assumed benefits of the VCI approach. For this use case, the pilots clearly preferred the VCI over a conventional PMD. The presented integration of a transparent 2-D top view into the natural 3-D egocentric out-the-window view via an AR-HMD proved to be a suitable approach and did not cause confusion or perception issues.

5.4.1 Evaluation Results

The subjective ratings clearly show that the pilots appreciate the advantages of a hover symbology in the form of a VCI. The positive results of the first study were confirmed by the more advanced second study with the JedEye HMD. Both the head-fixed and the mixed VCI variant appeared to be helpful and the evaluation did not reveal major differences between the two VCI positioning modes. It seems to depend on personal preferences which one was favored by the participant. Generally, the idea to couple the state of the VCI to the flight phase and the display content was perceived to be helpful. A possible conclusion from this result is that one could provide a number of feasible VCI options which can be selected depending on customer needs (defined in ConOps based on the task requirements). This great flexibility is one of the major benefits of such virtual instruments.

The positive reception of the VCI may seem expected because of the great advantage of the OAWD being always in sight, even when looking out the window. Nevertheless, one should also be aware of several potential limitations that this evaluation had to clarify. For instance, the readability of the see-trough, head-up VCI may suffer from its ever-changing background — the real world on which it is virtually overlaid. Insufficient luminance, lower angular resolution, and no available color are other issues that could have made the pilots choose the PMD instead of the HMD. However, the result confirms the author's hypothesis that the advantages clearly outweigh the drawbacks. The planned flight tests have to confirm that this is also the case for actual in-flight conditions (vibrations, more complicated light setting, etc.).

In good visual conditions (study I), no major differences in the achieved positional accuracy were found for the three top-rated VCI modes. As expected, the flight performance was already good with the conventional *AircraftFixed-HDD* variant so that the head-fixed and mixed options could not significantly improve the position holding accuracy. Nevertheless, the head motion data reveals that both variants with head-coupled VCI allowed the pilots to keep their heads up and eyes out at the obstacles significantly more often. This is an important safety gain in such maneuvers even though this quantity is not directly measurable with this simulator study.

Due to the limited outside vision system of the GECO simulator, the second study showed the advantages that the VCI-OAWD creates if the out-the-window view is restricted. As expected, the limited visual cues degraded the overall hover performance considerably. The hover accuracy with the VCI variants, however, was clearly better than with the PMD baseline condition.

The above-mentioned differences between study I & II highlight the potential of fully immersive VR-HMD-based flight simulators. Owing to their head-coupled FOV, they can provide an external view far beyond the capabilities of conventional outside vision projection domes. This means that simulators like the developed XR-Sim (Chap. 4) are able to better simulate the real out-the-window view, especially in confined area helicopter operations where far sideward and downward vision is required. However, it must be noted that the optics of current VR goggles cannot create collimated images like flight-certified HMDs and advanced outside vision projection systems.

A proven method to enhance the hover performance in DVE is to add acceleration cues to the display. However, such elements may capture a lot of attention and require excessive training before they can be used effectively. The author did not include such a symbol set as the developed symbology does not target zero visibility conditions. It is devised as an addition to outside visual cues, not as a replacement. The VCI-OAWD should enable the pilot to keep the eyes out with the supplementary OAWD always in sight. It should not fixate the pilot's attention on the symbology only. The pilot should not be animated to practice instrument-flying when actually operating under VFR.

The conducted research shows that the VCI appears to be a suitable alternative to a head-down OAWD. The pilots reported that it did not clutter their view but provided essential information in a user-friendly manner. However — at the current stage — this approach has not been experimentally compared to spatial auditory or haptic cueing. Every modality has individual strengths and weaknesses when serving as an OAWD. For instance, a visual display with a top-down view seems to be most powerful in providing precise distance presentation and an overview of a complex environment, e.g. with several widespread obstacles. A spatial audio warning, on the other hand, might be better suited to indicate a high-priority obstacle. It can intuitively and immediately guide the pilot's attention to an urgent threat location which might be outside of the pilot's current FOV. The human auditory distance perception is rather inaccurate, which is why pulse-period cueing is often used to synthesize distance (cf. parking assistants in modern cars) [201]. Additionally, haptic feedback via active inceptors/sticks can directly guide the pilot's control inputs. However, it does not provide the strategic overall picture of the situation like a visual top-down view. In the author's opinion, auditory and haptic cues can potentially enhance but not replace the VCI. The ultimate solution will be a multi-modal cueing system where the modalities complement each other. This claim is, for example, supported by Godfroy-Cooper et al. [112] who showed that an isomorphic spatial visual-auditory display was favored over visual-only and audio-only representations by helicopter pilots in DVE.

5.4.2 Avionics Integration and Path to Certification

The positive results raise the question: Which avionics systems are required to realize such a VCI-OAWD and what is their status quo from a regulatory point of view? Overall, the proposed pilot assistance system consists of a sensing, a processing, and a display subsystem. Regarding the obstacle sensing and data processing, Leonardo already offers an EASA-certified system [27]. Their OPLS meets the range and accuracy requirements of the selected offshore scenarios (see Sec. 2.2.6.1 for details). This work focused on the display subsystem, which comprises graphics processing hardware, a head-tracking system, and the HMD with its peripheral hardware. For the prototypical implementation of the VCI, actual avionics hardware was used: the Elbit JedEye as display unit (incl. head-tracking) and an industrial graphics platform from the project partner Diehl Aerospace Systems as graphics generation unit. For the realization of a VCI-based OAWS, one could basically keep Leonardo's sensor and processing units but replace their PMD with the HMD avionics described above.

Even though the hardware is available and certified, none of these systems allows for additional operational credit like reduced minima (see Sec. 2.2.3).

Nevertheless, they can be used as assistance systems which support the crew's situation awareness, reduce workload, and ultimately improve safety. Despite these benefits, many helicopters are still not equipped with such systems because the integration is often rather a question of business case than a lack of available technology. According to a survey conducted by the author [79], current German offshore helicopters are usually not outfitted with HMDs and OAWS. This may change if operational credit is granted by the authorities. In this regard, the recent efforts in working groups like the RTCA SC-213 and the EUROCAE WG-79 are encouraging and show that vision system topics are under active development in the standardization and regulatory organizations. The author is confident that if OAWS prove their reliability and usefulness in terms of safety increase under current regulations, an incremental introduction of additional permissions for certain scenarios can be discussed.

5.5 Recapitulation

This chapter presented the creation of flexible, task-adaptable *virtual cockpit instruments*, which are one major building block of the virtual cockpit envisioned in Chapter 3. The work features the development of a general VCI framework resulting in various positioning modes that define the behavior of the VCI. Within this project, the developed approach was successfully applied to address the DVE challenges of specific offshore hoist maneuvers.

To do so, a 360-deg obstacle awareness display was implemented as VCI on a state-of-the-art AR-HMD. This OAWD-VCI extends the established head-up symbology and makes currently important information easier available by transferring it from the conventional head-down display to the HMD. This allows the pilot to perform the hover maneuver "head-up, eyes-out" while simultaneously monitoring the OAWD. By means of two simulator studies — with 11 and 7 participants respectively — the author compared various VCI variants and confirmed that the VCI approach is very promising. In summary, the findings are:

- high subjective ratings for the VCI approach in general
- positioning modes *Head-Fixed* and task-/flightphase-adaptive *Mixed* are preferred over conventional PMD for hover maneuver

- similar hover accuracy with OAWD on PMD and VCI
- increased head-up, eyes-out times with head-fixed VCI (safety benefit)
- no clutter and readability issues were reported with the see-through HMD in the simulator (in-flight confirmation pending)
- VR-based emulation of see-through HMDs (XR-Sim setup II) proved to be a suitable approach for early symbology evaluations (like study I)

The experiments showed that the developed VCI-OAWD can be realized on flight-certified hardware, which makes it a potential mid-term solution (if flight trials and further tests confirm the current findings). With regard to the virtual cockpit, such a partial virtualization of cockpit instruments on an AR-HMD can be a first step towards a fully immersive flight deck where VCIs completely replace the conventional PMDs in the long term (cf. study IV).

Recommendations for future work on VCIs are made in Chapter 8.

Chapter 6

Study III — Synthetic Ocean Surface Representation[1]

A lack of usable outside visual cues is a critical issue for flight safety because it can lead to increased workload, loss of situation awareness, and — in the worst case — inability to control the helicopter. Typically, such problems are caused by adverse weather or comparable DVE conditions (see Fig. 1.1). In offshore environments, however, such a shortage of visual references appears to be an inherent issue even in VMC. The main reasons are that only few fixed objects exist and that the ocean surface rarely offers usable optical flow and ground texture cues (see Sec. 3.4.3).

A virtual cockpit enables the HMI designer to create a virtual version of the environment that suits the pilots' needs better than the real surroundings (see Sec. 3.2.2). The work presented in this chapter shows how this can be applied to solve the issue stated above. In summary, the goal of study III is to:

> Explore the potential of a VR-HMD-based view of the surroundings by developing a synthetic ocean surface representation that provides more valuable visual cues than the natural appearance of the sea.

[1] Parts of this chapter have been published by the author in [71, 77].

The developed symbology is inspired by state-of-the-art terrain representations (see Sec. 2.2.6.2) which are adapted to the specifics of the offshore use case. The following sections describe the symbology development (Sec. 6.1) and its evaluation (Sec. 6.2–6.4) by means of a human factors study in the XR-Sim. The main findings from this chapter are summarized in Sec. 6.5. The novel ocean surface symbology is an integral part of the fully virtual cockpit presented in Chapter 7.

6.1 Providing Better Cues with a Synthetic External View

The goal of this work is to create a computer-generated out-the-window view that improves the pilot's ability to control the helicopter and fly over open water. To achieve this aim, the author follows an **ecological approach** [111, 209, 347] in the sense that the created virtual world provides visual cues in a way that pilots naturally use when they fly in good visual environment.

6.1.1 Requirements Analysis

The out-the-window view is an invaluable information source for pilots flying in good visual environment. The horizon, terrain features, man-made or natural objects, and ground textures create visual cues like optical flow or parallax, through which the pilots — consciously or unconsciously — perceive their egomotion and control the helicopter within the 3-D space [348]. The pilot interviews in Sec. 3.4.3 revealed — however — that only a few of these cues are available in an offshore environment [78]. The all-dominant visual element is the ocean surface, which rarely supplies usable cues. Due to its own movement, the sea does not constitute a fixed visual reference and often provides more misleading motion cues than valuable information. Looking at the ocean surface only, pilots cannot hold their position during hover as the moving waves lead to wrong motion perception.

Moreover, it is essential for an offshore pilot to know where the wind is coming from and how strong it is because the wind strongly influences the performance of the helicopter. If at all possible, landings are conducted with headwind. Experienced offshore pilots stated that they can estimate wind direction and speed from the shape of the sea surface. Under calm wind conditions, the water looks like a mirror. At higher wind speeds, larger waves with spray appear and foam streaks move in wind direction. A well-known classification of wind speeds and the corresponding appearance of the sea is given by the Beaufort scale [196].

In conclusion, this gives two major requirements for the synthetic ocean surface representation to be developed:

1. usable visual references for the pilots to better perceive their motion,
2. information about wind direction and speed.

Following this plan, the novel symbology will offer all information that the real sea surface provides and additionally replace the drawbacks like adverse motion cues with more useful visual references.

6.1.2 Background on 3-D Perception & Related Work

The human perception of 3-D space generally relies on two co-existing mechanisms [347]: **Direct perception** happens relatively automatically through the ambient vision and helps to sense and control the egomotion. By contrast, **indirect perception** demands greater attentional resources to judge the depth and distance of objects in the 3-D environment.

The mechanisms of egomotion perception and the application of this knowledge to vision system displays have been researched extensively for several decades [e.g. 97, 103, 165]. Six **optical invariants** were identified to be important for the direct perception of egomotion: compression (texture gradient), splay, optical flow, time-to-contact (tau), global optical flow, and edge rate [111, 347]. This leads to the conclusion that a synthetic representation of the out-the-window view must provide these cues in order to be *ecological.*

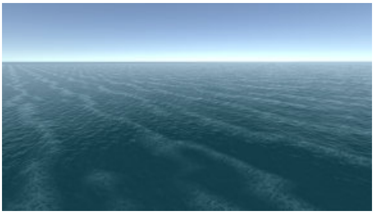
According to Hoh [130], the cue-providing elements of a scene can be classified into **macrotextures** (large objects) and **microtextures** (fine-grained details). The literature review in Sec. 2.2.6.2 shows that state-of-the-art displays create synthetic versions of both texture types. See-through HMD symbologies mainly use macrotextures because microtextures would heavily occlude the reality behind the display and probably cause clutter issues [323].

Examples are terrain grid overlays and contour lines [58, 213, 326], conformal outlines and virtual prisms around the landing pad [215, 268], and virtual hover boards [12, 323]. In contrast, PMDs provide microtextures by means of real-time camera images [295] or synthetic ground textures [24, 213, 270], often augmented with the macrotexture elements mentioned above. However, the cues on the PMD cannot be as effective as the real-world cues since they do not cover the pilots' peripheral vision, which is essential for direct perception [347]. Another difference between current HMD and PMD symbologies is that the former are mostly made for monochrome displays, whereas the latter are full-color representations.

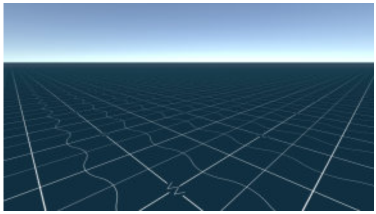
The proposed VR-HMD symbology can combine the best features of PMDs and AR-HMDs by creating a full-color representation with no see-through issues on a fully immersive, conformal display. Synthetic ground textures and grid overlays are common approaches to generate the required cues (e.g. splay, optical flow, edge rate, etc.). These seem to be suitable concepts also for a virtual ocean surface representation. However, the approaches have to be adapted because the focus of previous work has been on the illustration of onshore environments and mountainous terrain in particular.

6.1.3 Symbology Implementation

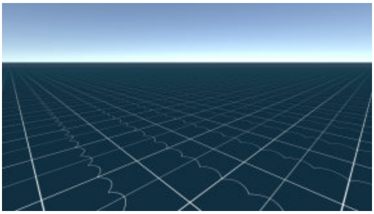
Four symbology variants were developed and implemented with the XR-Sim. As shown in Fig. 6.1, the first symbology — called *Natural* — is strongly influenced by the appearance of the real sea. The others are more abstract representations. Their degree of abstraction varies from uniform, wave-like 3-D meshes called *Elevated* to simple, flat surfaces with special grid structures (*Flat-Round*, *Flat-Peak*). All variants have in common that they are static, which means that no moving waves are presented. This reduces clutter and provides a fixed visual reference for the pilots to perceive drift motions. The synthetic water surface is positioned at sea level, where the pilots would see the real ocean surface in good visibility without wearing the immersive goggles. Further, all representations show the wind force in four discrete levels corresponding to certain wind speed ranges.



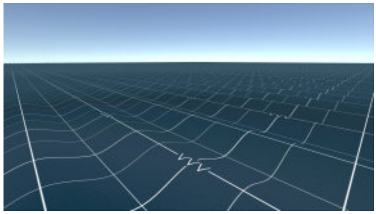
(a) The *Natural* symbology displaying a wind strength of level 3. The wave patterns are oriented perpendicular to the wind direction.



(b) The *Flat-Round* display in wind condition 2. The two arrowheads and the appearance of the wave line indicate wind direction and strength.



(c) The *Flat-Peak* representation indicating wind strength level 2. The peaks display wind strength and direction.



(d) The *Elevated* symbology under wind condition 3. High waves and three arrowheads indicate strong wind.

Figure 6.1 – The developed ocean surface representations (wind from around 45°, from the right back to the left front in the images) [71, 77].

6.1.3.1 Description of the Developed Symbologies

Natural The *Natural* representation incorporates elements from real water but only to a certain degree. It comprises waves and the typical light refraction and reflection. This follows the idea that the pilots should intuitively perceive the wind characteristics via the familiar appearance of the water. However, the waves are static so as to prevent adverse visual motion cues.

Flat-Round The *Flat-Round* display variant is a modified regular grid. The water surface is represented by a flat blue-colored surface. The grid lines are oriented parallel (and perpendicular) to the wind direction. Every second grid line perpendicular to the wind is replaced by a wavelike line. Regularly-spread arrowheads point in the direction of the wind. The wind force is conveyed via the number of arrowheads. Additionally, the amplitude of the curvy line is increased and the wavelength is reduced for stronger winds.

Flat-Peak *Flat-Peak* is related to *Flat-Round* as it is also based on a flat surface with a regular grid overlay. However, the arrowheads and the sinusoidal line are replaced by an undulated line with peaks on one side. The peaks indicate the wind direction like the arrowheads do in the *Flat-Round* design. The wind strength is shown by the number of the peaks and the amplitude of the “wave”-line.

Elevated In contrast to the other layouts, the *Elevated* design is not flat. It is made of a three-dimensional mesh with a uniform and steady wave structure. Moreover, the display comprises a regular grid oriented with the wind direction. The wave crest lines are straight and run perpendicular to the wind direction. The arrowhead symbology used by *Flat-Round* is also applied in this display variant to show wind direction and strength. Additionally, the wave height increases with the wind speed.

6.1.3.2 Applied Design Principles

Previous research found advantages for displays that integrate information spatially into the environment [183]. This display design principle is called **scene-linking**. The developed symbologies apply this knowledge by presenting the wind information in a scene-linked manner. Instead of an abstract display of wind speed and direction as numbers on a PMD, the wind information is coded into the appearance of the synthetic ocean surface via grid features, arrows on the ground, et cetera. Mapping the wind direction directly into the 3-D world also relieves the pilots from the mental integration effort which is usually required to transform the world-referenced, digital wind direction value into the ego-referenced space that the pilot acts in.

Further, the various wind information representations follow the **proximity compatibility principle** [341] as they combine wind direction and wind strength into a single indication via “object integration”. For instance, *Flat-Round’s* sinusoidal line integrates both parameters via its orientation, wavelength, and amplitude. Also, the arrowheads show both in one.

The detailed water surface graphics of *Natural* offer a high amount of **micro-texture**. In strong wind conditions, the waves also provide some degree of

macrotexture. However, not as structured and clear as the cues of a grid. The grid of the abstract variants provides a wide-area, world-fixed macrotexture that generates egomotion cues like (global) optical flow, edge rate, splay, and depression (cf. [97, 165]). Additionally, the dark blue background is not entirely smooth and blank but offers a fine-grained structure which serves as microtexture when the pilots operate close to the ground.

Natural and *Elevated* follow Roscoe's **principle of pictorial realism** [257] as the water representations reflect important characteristics of the real ocean surface in different wind conditions: Rough water textures and high synthetic waves correspond to stronger wind. Still, the synthetic representations do not aim for photo-realism. This considers the ideas of Smallman and John [281], who state that **naive realism** often does not result in the best performance, even though most users prefer a perfectly realistic representation.

6.1.4 Required Data Sources

The ocean surface representation requires data about wind speed and direction. Especially the latter has to be low-pass filtered to ensure a stable, non-distracting symbology. Additionally — as for all synthetic vision systems — a reliable source of ownship position and orientation as well as the height of the sea surface is needed. Finally, the ocean surface representation is not a standalone solution but only a part of a larger external vision system, which must — of course — integrate data about the rest of the environment including fixed and moving obstacles. These data source requirements are discussed in the following study IV (Sec. 7.1.5) where the ocean surface symbology is integrated into advanced 3-D perspective views.

6.2 Evaluation Method

The value of the developed symbologies was assessed with an experiment in the XR-Sim. The main research goals for this study were to 1) get general feedback on the idea of the synthetic ocean surface representation, and to 2) compare the developed variants with regard to the pilots' ability to understand the displayed wind information and perceive their egomotion.

6.2.1 Participants

Nine male pilots with an average age of 36 (range from 25 to 60) participated in the study. Six subjects flew both military and civil aircraft while three had civil background only. The mean flight hours of all subjects was 2236 h (min: 215 h, max: 6200 h). Regarding licenses, two owned a PPL, four a CPL, and three an ATPL. Four pilots had a mean experience of 18.5 h with head-worn displays in flight. Six participants wore a VR headset like the Oculus Rift before (7.2 h on average). All subjects had normal or corrected to normal vision.

6.2.2 Apparatus

The experiment took place in DLR's GECO using the XR-Sim configuration mode V with the Oculus Rift CV 1. Chapter 4 provides details about the XR-Sim, the VR goggles (Sec. 4.2.4), and the used setup mode V (Sec. 4.3, Fig. 4.5a). The outside vision system and the flight deck instrumentation of the GECO were disengaged since the participants wore the non-see-through HMD throughout the test runs.

As flight simulation, DLR's EC135 command model was employed. A thorough explanation of this modern control augmentation system and its various upper modes is given in Sec. 4.2.2. For this experiment, the following command types and hold modes were applied to the four flight control axes: *acceleration command, airspeed hold* for the longitudinal cyclic axis, *attitude command, attitude hold* for the lateral cyclic axis, *turn coordination* for the pedals, and *vertical velocity command, height hold* for the collective. The impact of the wind was intentionally not eliminated by the control system. Thus, the wind caused the aircraft to drift in crosswinds and to lose ground speed when turning into the wind.

6.2.3 Task

In each test condition, the pilots conducted a flight that was split into two parts. The first segment was started in-flight, 500 ft over water with 60 knots ground speed. The participants were instructed to: 1) judge the wind direction based on the water representation, 2) turn the helicopter into the wind, 3) adjust the airspeed to maintain 60 knots ground speed when turned into the wind. The second segment was an approach to an offshore platform. The pilots had to perform a 90° turn into the wind and conduct a straight approach. Segment 2 was started in-flight (500 ft above helipad elevation, 80 knots airspeed) with the landing pad located at 2 or 10 o'clock (varied randomly).

6.2.4 Tested Symbology

During the whole experiment, no flight instruments except for the developed ocean representation were available. The pilots had an unobstructed view of the surroundings without any cockpit structure displayed around them. Also, the only object in the synthetic environment was the offshore landing deck during the approach scenario. This implies that the ground speed estimation during the first segment could only be based on the water representation. For the approach task, pilots could use both water symbology and the offshore platform to manage their glide path and speed. Further, no virtual representations of the flight controls or other real cockpit elements were displayed.

6.2.5 Experimental Design & Procedure

The experiment applied a within-subject design with two independent variables: 1) display type and 2) wind condition. The display variable comprised the four ocean representations described above: *Natural*, *Flat-Round*, *Flat-Peak*, *Elevated*. The wind variable had four levels represented by the wind speeds 0 knots, 8 knots, 20 knots, and 35 knots (each combined with a random wind direction). This resulted in a total of 16 experimental conditions per pilot: 4 displays × 4 wind conditions. The four flights with the same display condition were flown in a row. The order of these display blocks and the wind condition sequence was counterbalanced between the participants. In total, 144 flights (9 pilots × 16 conditions) were performed for this evaluation.

The whole test session including briefing, training, testing phase, and debriefing lasted around three hours. The testing phase was conducted in two blocks of eight flights separated by a 15 min break.

6.3 Evaluation Results

This section summarizes the most important findings from the study. First, an overview of the pilots' feedback on the developed ocean surface representations is given. Second, several measures compare if the pilots were able to understand the presented wind information and perceive their egomotion.

During the experiment, the aircraft state and flight path as well as head-tracking data was recorded. Further, the participants provided subjective feedback via custom-made post-flight and debriefing questionnaires. The data analysis was carried out with MATLAB [182] and the statistical computing environment R [249]. An α level of .05 was adopted for significance.

6.3.1 General Pilot Feedback

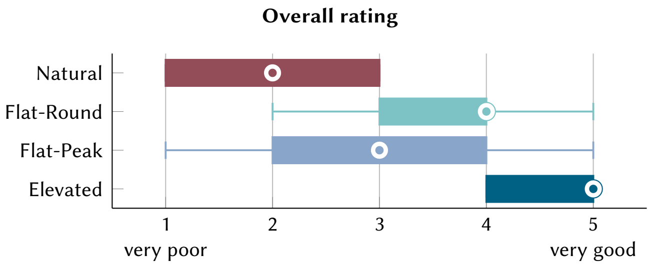


Figure 6.2 – Overall rating of the developed ocean surface representations [77].[2]

During the debriefing, the pilots gave an overall rating of the developed symbologies. This high-level comparison is depicted in Fig. 6.2. A repeated-measures analysis of variance (ANOVA) revealed significant differences in the overall rating between the four ocean surface representations, $F(3, 24) = 17.435$, $p < .001$, $\eta^2 = .554$. With all scores between 4 (“good”) and 5 (“very good”), *Elevated* was clearly favored over the other symbologies (*Natural*: $p < .001$, *Flat-Round*: $p = .025$, *Flat-Peak*: $p < .001$). Tukey post hoc tests also showed that *Natural* was perceived significantly poorer than all other

[2] Boxplots show median (dot/circle), 25th and 75th percentiles (filled rectangle), and outliers (x markers) with whisker length 1.5 interquartile range.

variants (*Flat-Round*: $p < .001$, *Flat-Peak*: $p = .009$). The scores of *Flat-Round* and *Flat-Peak* range in between while the results of the latter are spread across the whole scale indicating strong disagreement between the subjects on the value of this symbology.

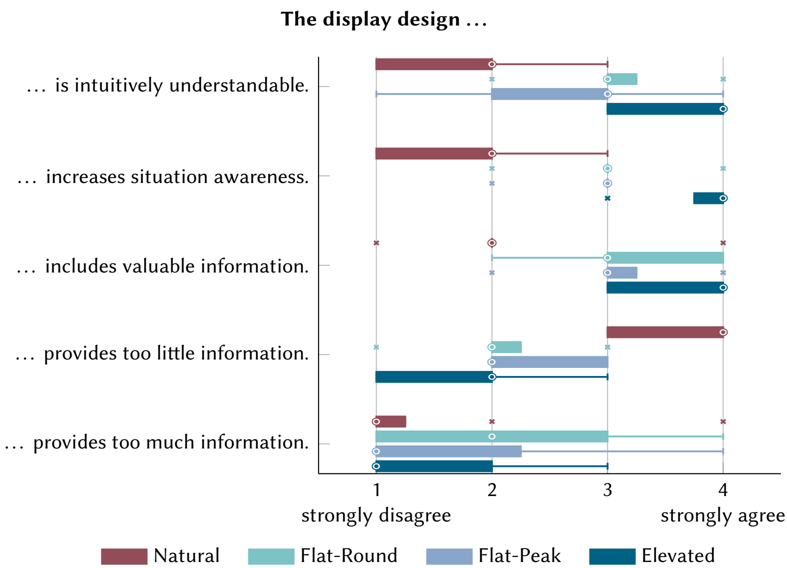


Figure 6.3 – Pilot feedback on the display design.[2]

Other results from the debriefing questionnaire show the same tendencies as the overall ranking. As can be seen in Fig. 6.3, *Elevated* was rated as most intuitively understandable and was perceived to best increase situation awareness. The height and orientation of the waves in this design were acknowledged as a clear indication of the wind conditions. Also, *Flat-Round* appears to be a good option, whereas *Flat-Peak* and its wavy line were rated not intuitive by many participants as it could be interpreted as wind from both perpendicular directions. *Natural* was not perceived intuitive nor did it help to gain situation awareness.

Regarding the general display design concept, all pilots but one agreed that displaying wind direction and speed via a grid symbology is useful. One pilot remarked he requires the wind speed as a number while other participants said that the approximated/discrete strength indication via the number of arrows is sufficient. Further, 7 of 9 pilots stated that they prefer the wind indication arrows pointing downwind ("status display", as presented in the experiment) over arrows pointing in desired flight direction ("command display"). Reasons were that they are used to this from weather reports and map displays. Another argument against a command display is that one does not always fly against the wind.

6.3.2 Wind Information and Egomotion Perception

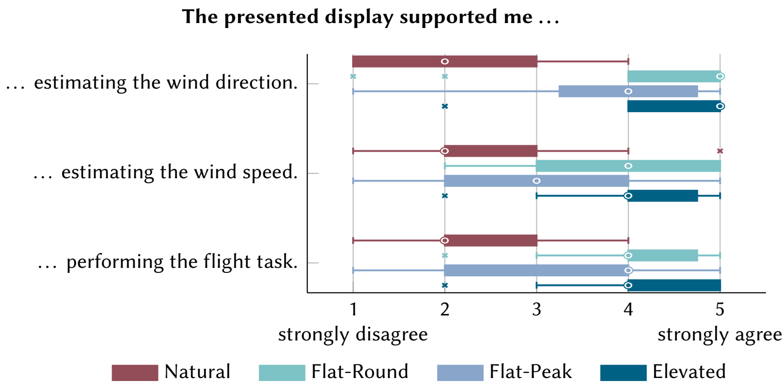


Figure 6.4 – Symbology ratings from the post-flight questionnaire.[2]

After each flight, the participants stated if the presented symbology supported them during the past run. Figure 6.4 illustrates the accumulated results. It indicates the degree of support the pilots got for the estimation of wind direction and speed as well as for the execution of the flight task. For each aspect, the *Natural* symbology was ranked lowest with most pilots disagreeing with the statements presented in the questionnaire. *Flat-Round* and *Elevated* were rated best regarding all three criteria. Their scores range around 4, which means "agree to the statement". *Flat-Peak* falls somewhat short of these symbologies.

[2] Boxplots show median (dot/circle), 25th and 75th percentiles (filled rectangle), and outliers (x markers) with whisker length 1.5 interquartile range.

The pilots were asked to read the wind direction from the presented symbology, turn the helicopter against the wind, and tell the experiment leader when they thought the head-wind heading was reached; at this time, the deviation from the desired “headwind-heading” was measured. On this data, a two-way repeated-measures ANOVA with the independent variables symbology type and wind condition was performed. No significant main or interaction effects on the heading accuracy were found.

For further assessment, the obtained data was classified into four groups. If the pilot deviated less than 2°, the flight was categorized as “desired”. Deviations up to 10° correspond to “adequate”. “Front-back” represents flights where the pilots turned not into but out of the wind and flew a heading directly opposite of the desired direction with tailwind. The graphs in Fig. 6.5 indicate that *Natural* achieved fewer results in the “desired” range than the other display types. Additionally, more “out of bound” flights were observed under this condition. *Flat-Round* and *Elevated* seem to be relatively equal as both generated at least 89 % “desired” flights. Interestingly, the *Flat-Peak* variant also had a high number of “desired” and “adequate” flights but showed a number of front-back confusions. This means that the pilots flew in directly opposite direction.

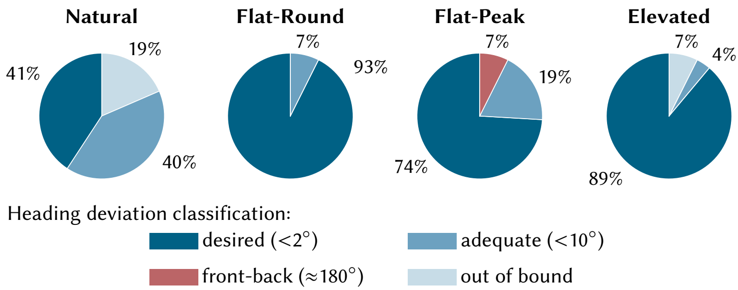


Figure 6.5 – Accuracy reached when turning into the wind based on the developed ocean surface representations [71, 77].

After turning into the wind, the pilots were instructed to adjust the airspeed to maintain 60 knots ground speed. As no flight instruments were displayed, the subjects had to judge the speed visually from their motion relative to the ocean surface representation. The deviations from the wanted ground speed are plotted in Fig. 6.6. Each flight is represented by one horizontal line in the

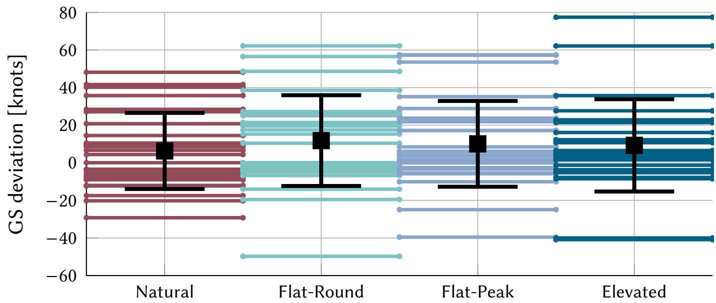


Figure 6.6 – Deviations from the desired ground speed for the developed display variants [71].

plot. The black squares depict the mean values while the whiskers correspond to the standard deviation. The obtained deviations from the desired ground speed were spread between −50 knots (too slow) and +77 knots (too fast). On average, pilots flew faster than desired and nearly half of the flights produced deviations larger than 15 knots. Similarly, the participants had problems managing their speed during the approach to the offshore platform in the second segment of the flight. The plots do not show clear differences between the four display conditions. A repeated-measures ANOVA revealed no significant influence of the symbology type but a significant main effect of the wind condition, $F(2, 16) = 6.151$, $p = .010$, $\eta^2 = .146$. The data shows smaller speed deviations for lower wind speeds. However, post hoc tests could not confirm this finding.

6.4 Discussion of the Evaluation Results

Recalling the two goals that were defined for the symbology development, the discussion should review if the tested designs adequately provided

1. usable visual references for the pilots to better perceive their motion,
2. information about wind direction and speed.

Regarding the latter, statistical tests could not identify significant flight performance differences between the symbology variants. Despite this, a closer look at the data in terms of the heading accuracy classification revealed important issues leading to the conclusion that all three abstract display variants (*Flat-Round*, *Flat-Peak*, *Elevated*) are favored over the *Natural* layout. This is also confirmed by the subjective results. With all abstract variants, the pilots could turn into the wind very precisely. However, *Flat-Peak* was found prone to 'front-back-confusion'. That is that the pilots interpret the symbology as wind coming from the back while in fact they fly into the wind. It has to be noted that the pilots often realized an initial misinterpretation during the flight and corrected it before the end of the task. Thus, the actual number of initial front-back confusions was higher. The questionnaires indicate a clearer advantage for the *Elevated* symbology than the objective results. Pilots liked the emphasized and intuitive presentation of the wind information via the height and orientation of the waves. However, this representation is visually very compelling and might unnecessarily draw attention. As *Flat-Round* achieved the same objective performance with a much simpler design, this might be the better option if one aims for a representation that is "as easy and simple as possible." The pilots' preference for the more realistic *Elevated* may also be explained by Smallman's [281] concept of naive realism.

Regarding usable visual references for motion perception, the abstract grid representations also outperformed the *Natural* display. Several pilots stated that they estimated the wind direction and speed not only based on the presented icons. Instead, they also based their decision on the wind-induced drift of the helicopter. The grid served as a fixed reference on the ground which is usually not available over water. The generated optical flow cues made it easy to visually recognize even small drift velocities caused by side wind components. This means that the pilots used *direct perception* [347] to judge the wind direction as they processed the optical flow created by the static ground representation, without interpreting the arrows of the symbology. In conclusion, a grid even without additional wind indications would still be very helpful.

Even though the grid drastically improves the perception of drift motion, it seems not to be sufficient to judge the own ground speed. None of the tested symbologies enabled the pilots to adequately maintain 60 knots after turning into the wind. This can have several reasons. Most probably, the pilots perceived the velocity cues (i.e. global optical flow and edge rate) of the grid lines passing by, but they could not relate this impression to the desired ground speed of 60 knots. The run was started at that speed to give them an idea of how the respective egomotion cues look like. However, this and the pre-experiment training seemed not to be enough to successfully conduct this task. Another factor that might have impaired the speed estimation is the restricted peripheral vision: The Oculus Rift provides only around 100° of horizontal FOV, which leaves about 50° on both sides occluded and black. As discussed above, the direct perception of egomotion depends on visual cues from all over the visual field [347]. So maybe the FOV of the used HMD was not large enough to effectively support this type of human perception. However, one can argue that in a real scenario the pilots would have additional air- and ground-speed indications providing them with exact values. Future work should further investigate the egomotion perception mechanisms in such a virtual environment. Furthermore, the value of such a computer-generated out-the-window view should be quantified compared to a real-world baseline.

6.5 Recapitulation

This chapter presented the development of a *synthetic external scene representation* — one of the main components of the virtual cockpit devised in Chapter 3. The work shows how one can make use of the properties of a non-see-through HMD to create a virtual environment that provides more valuable information and visual cues than its real-world counterpart. Here, this was demonstrated by the example of a synthetic ocean surface representation for helicopter offshore operations. It provides wind information in a scene-linked manner and offers cues for egomotion perception. With his implementation, the author demonstrates how established display design principles and concepts from state-of-the-art PMD and AR-HMD symbologies can be transferred to a virtual cockpit.

The developed ocean surface representations were compared via a pilot-in-the-loop study in the XR-Sim. In short, the experimental findings are:

- pilots approve the scene-linked display of wind information via the synthetic ocean surface
- abstract visualization variants are clearly preferred over the *Natural* layout (subjective and objective measures)

- *Elevated* and *Flat-Round* are most promising as *Flat-Peak* is prone to front-back-confusion
- follow-up research on visual cues for egomotion perception is needed

The resulting ocean surface symbology is one building block for the final study on advanced ego- and exocentric views in Chapter 7. Recommendations for future work on external scene representations are given in Chapter 8.

Chapter 7

Study IV — Advanced Ego- and Exocentric Views[1]

The restricted out-the-window view was identified as a major problem for helicopter pilots operating in confined areas, for instance during offshore maneuvers (see Sec. 3.4.3). The OAWD used in the VCI studies I & II is an example of how a 2-D top view in addition to the pilot's natural 3-D egocentric perspective can improve the spatial awareness. The work conducted here follows a different approach as it does not add a second view but completely replaces the natural out-the-window view with an advanced, computer-generated view through a VR-HMD. With regard to the author's virtual cockpit continuum (Fig. 3.1), this is a more virtual solution than the VCI approach seen before.

As discussed in Sec. 3.2, the usage of a VR-HMD allows the HMI designer to fully control what the pilot sees. This chapter puts this potential of the fully virtual cockpit into practice. The overall aim of study IV is to:

> Explore the capabilities of a fully immersive, head-worn display and develop non-conventional ego- and exocentric views that solve the DVE issues regarding fuselage-restricted cockpit view and adverse pilot eye point.

[1] Parts of this chapter have been published by the author in [68, 74, 77].

The following Sec. 7.1 describes the development of several non-conventional 3-D perspective views. An egocentric cockpit view with a semi-transparent aircraft structure tackles the problem of the fuselage blocking the view. Tethered,[2] exocentric views virtually change the pilot's eye point location to generate a better view of the surroundings. To further enhance these perspective views, the author used conformal and scene-linked symbology — approaches that are well-known from state-of-the-art flight guidance displays (see Sec. 2.3). Additionally, the new display types apply the findings of the preceding studies I – III as they integrate the developed synthetic ocean surface representation and a VCI showing a PFD. Sections 7.2–7.4 present a pilot-in-the-loop experiment that shows the advantages and limitations of three novel views compared to a conventional cockpit view. Finally, Sec. 7.5 summarizes the main findings and draws conclusions.

7.1 Increasing Spatial Awareness with 3-D Ego- and Exocentric Views

What is the problem to be solved? Hovering and landing a helicopter in a confined area — for instance next to offshore installations — involves the following main tasks:

1. control — stabilize the helicopter,
2. guidance — direct the aircraft to the desired position,
3. conflict detection — detect and avoid obstacles and other hazards.

With regard to Sec. 2.4.2, task 1 and 2 require displays that support **local guidance**, while task 3 needs **global awareness**. According to the author's task analysis in Sec. 3.4.3, all three functions are complicated by DVE issues. Controlling and stabilizing the helicopter (task 1) is impeded as only a few usable outside visual cues are present. This problem was already addressed by the development of the cue-providing synthetic ocean surface, which is why this symbology is used again as part of the perspective views developed here. The focus of this study, however, is on how to improve the spatial awareness and the performance of task 2 and 3, which are seriously complicated by two **operation-specific DVE issues** (see Fig. 1.1): The own aircraft structure as

[2] Refer to Sec. 2.4.1 for an explanation of this term.

well as the adverse pilot eye point both hinder the view of the desired position (task 2) and the detection of nearby obstacles (task 3).

Which approach does this work follow to solve the problem? While pondering over this problem, the author realized that a **combination of a fully virtual cockpit with a non-conventional 3-D perspective view** could be a solution. A fully virtual cockpit view would come with many potentials: a large, full-color stereo display, a real-world-aligned view in which the pilot can naturally look around, and finally full control and many options for the display designer to show an advanced external view[3]. The advantages of the various available 3-D perspectives on the other hand were extensively reviewed in Sec. 2.4. In a nutshell, the cited literature reveals that **egocentrism** is better for local guidance functions like task 1 & 2, whereas **exocentrism** better supports global awareness (task 3). Based on that knowledge, the author decided to implement and to compare two distinct approaches:

1. **Transparent cockpit view** — retains the familiar egocentric viewpoint, which is good for local guidance and control, but improves the outside vision by rendering the cockpit structures semi-transparent in the virtual view.
2. **Tethered view** — combines an exocentric viewpoint with an egocentric frame of reference (cf. Fig. 2.21), which represents a good compromise between egocentric local guidance and exocentric global awareness.

What is new compared to related work? Ego- and exocentric flight guidance displays are not a new idea. This work builds on the existing knowledge while introducing several novel aspects. The first important difference is the **display type**: Related work[4] renders the perspective projection on a rather small 2-D PMD screen, whereas *here* a real-world-conformal view on a VR-HMD is presented. This involves several new design considerations because the view is now coupled to the pilot's head movement, the geometric field of view is pre-defined by the HMD, and better depth cues are available (details see Sec. 3.2.1 and 3.2.2). The second difference is the **field of application**: Previous research dealt with taxiing and approach of fixed-wing aircraft (see Sec. 2.4.3). Obviously, this poses different challenges than helicopter-specific tasks like hovering and landing in close proximity to obstacles. Finally, the

[3] Refer to Sec. 3.2 for the author's in-depth discussion of these potentials.
[4] A detailed literature review is provided in Sec. 2.4.3.

3-D perspective views developed here are used as the **primary and only view**, while existing PMD-based displays are an addition to the pilot's natural, egocentric out-the-window view. Because of these differences, one cannot just transfer the previous findings without conducting further research.

7.1.1 Implementation of a Transparent Cockpit View

The central advantage of a virtual cockpit is that the computer-generated world can be shaped according to the pilot's needs. This means that a virtual cockpit would probably not replicate a conventional cockpit as this is always a trade-off between pilot needs and other requirements from engineering, aerodynamics, et cetera. For instance, pilots criticize that many non-transparent parts of the aircraft structure degrade their view of the surroundings in several directions. As described before (e.g. Sec. 1.1 and 3.4.3), they can hardly see what happens below, above, and behind the helicopter. Even the forward view is restricted by the instrument panel, especially with pitch-up attitude.

Based on these considerations, the author devised the transparent cockpit view shown in Fig. 7.1. Several view-blocking structures are removed and only a minimal airframe is rendered. To avoid occlusions, all remaining elements are made semi-transparent. Thus, the pilots virtually see through the fuselage. Instead of seeing the cockpit floor when looking down, they see potential obstacles, a person to hoist, or the desired landing area. It is important to note that the airframe is not rendered fully transparent because it is a necessary reference for the pilot's attitude perception. Whether the chosen degree of transparency and the selection of rendered elements are suitable for this task, is evaluated in the following simulator study. Additionally, the transparent cockpit view includes a computer-generated external scene (in this study the ocean surface representation from Chapter 6). Compared to the conventional out-the-window view it comes with all the advantages and limitations that were thoroughly discussed in Sec. 3.2 and 3.3.

In summary, the transparent virtual cockpit tries to improve the pilot's spatial awareness by providing an unrestricted 360-deg view. However, it does not solve the problem that the conventional eye point may be inappropriate to look at objects far below or even behind the aircraft while simultaneously having to fly the helicopter. This is addressed by the tethered view developed in the following.

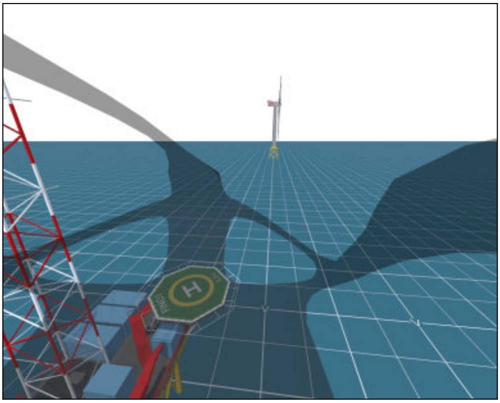


Figure 7.1 – Pilot's view in the developed transparent cockpit. Note that the landing area, which would be occluded by the fuselage, is now visible through the semi-transparent airframe. Virtual instruments (Chap. 5) can be added based on task requirements (own figure).

7.1.2 Development of a VR-Based Tethered View

As introduced in Sec. 2.4.1, a tethered view has an exocentric viewpoint which shows the ownship as seen from a following aircraft. The appearance of the tethered view is defined by the following parameters:

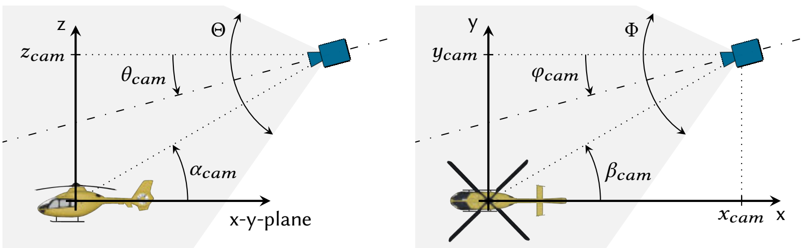
- viewpoint or camera position,[5]
- view direction or camera orientation,
- geometric field of view (GFOV),
- camera frame of reference.

Several researchers[6] have evaluated how to optimally choose these parameters to get the best pilot performance — for their specific use case. However, due to the above-mentioned fundamental differences between the scenarios and the display format, this thesis must determine its own "optimal" parameters. This process is described in the following.

[5] In computer graphics terminology, the viewpoint is usually referred to as the position of the (virtual) camera, which shoots the image to be displayed to the user (see also Sec. 2.4).
[6] Refer to Sec. 2.4.3 for the author's literature review.

7.1.2.1 Viewpoint/Camera Position

In the literature, it is common practice to define the camera position in spherical coordinates. For instance, Theunissen et al. [310] use the terms *lever arm length*, *azimuth*, and *elevation*. Similarly, this thesis uses the distance between camera and helicopter $d_{cam} = \sqrt{x_{cam}^2 + y_{cam}^2 + z_{cam}^2}$, the elevation angle α_{cam}, and the lateral rotation of the camera around the helicopter β_{cam}, as sketched in Fig. 7.2. The spherical notation $(d, \alpha, \beta)_{cam}$ can be converted to Cartesian coordinates $(x, y, z)_{cam}$ using the standard conversion formulas (analog to Eq. (5.1)). As a side note, since this is a head-coupled HMD view, the translational movement of the pilot's head will be added to this initial viewpoint position. However, these dynamic changes of the camera location are small compared to the overall positioning described here.



(a) Side view. **(b)** Top view.

Figure 7.2 – Illustration of the parameters defining the exocentric, tethered view: viewpoint/camera position in Cartesian $(x, y, z)_{cam}$ or spherical $(d, \alpha, \beta)_{cam}$ notation, head/camera rotation θ_{cam}, φ_{cam}, and vertical and horizontal field of view Θ, Φ (own illustration).

The camera distance d_{cam} is like a zoom factor representing a trade-off between spatial resolution and visible range [310]: The smaller it is, the larger appears the helicopter and the higher is the resolution of its immediate surroundings. On the other hand, a closer view means that a smaller range around the helicopter is visible. The elevation angle α_{cam} defines the "mixing ratio" between vertical and horizontal plane in the 3-D view. In other words, the higher α_{cam}, the better the perception of horizontal distances and the worse the estimation of vertical relations like altitude. At the extrema, $\alpha_{cam} = 90°$ represents a top view like a map and $\alpha_{cam} = 0°$ only shows the vertical plane. A carefully chosen value for α_{cam} enables the pilot to perceive both the horizontal and the vertical plane within a single view (with the cost of line of sight (LOS) ambiguity discussed in Sec. 2.4.2). Finally, the azimuth angle β_{cam} allows to position the camera sideways, not directly behind the ownship. For forward flight of a manually controlled helicopter, it seems best to have the camera position and default viewing direction in line with the longitudinal aircraft axis. A non-zero β_{cam} might have benefits in low-speed, sideways maneuvering with a highly automated helicopter, where the pilot task shifts from manual flying to high-level commanding or supervision. After several hands-on tests in the simulator, the viewpoint was set to $\alpha_{cam} = 25°$, $\beta_{cam} = 0°$, and $d_{cam} = 19\,\text{m}$ for the following pilot-in-the-loop evaluations.

7.1.2.2 Camera Orientation and Geometric Field of View

The horizontal and vertical GFOV (Φ, Θ) determine the extent of the view. This so-called view frustum is represented by the gray area in Fig. 7.2. The viewing direction and therefore the attitude of the view frustum is defined by the camera orientation $(\psi, \theta, \varphi)_{cam}$. A major difference to the known PMD-based tethered views is that these parameters are *not* freely chosen in the HMD-based virtual cockpit.

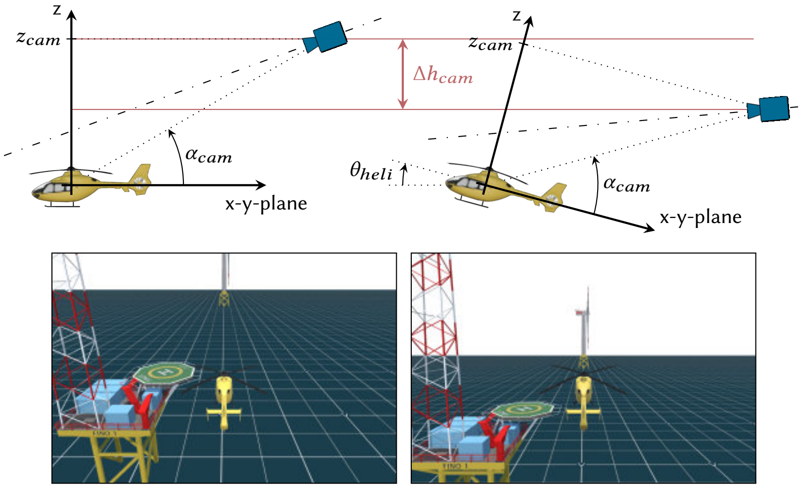
Being a real-world-conformal view, the GFOV is fixed by the DFOV of the HMD (see Sec. 3.3.1.1). The orientation of camera and frustum, on the other hand, is coupled to the pilots' head rotation. This is a significant difference and also an important advantage over the PMD because it enables the pilots to naturally look around in the synthetic environment by turning their head. For tethered views on PMDs, the camera orientation is — if at all — only changeable via a dedicated input device. This will rarely be as intuitive as turning the head. Changing the viewing direction by rotating the head is what humans do throughout their life.

Finally, what has to be explicitly set for the head-coupled exocentric view is the default viewing direction when the pilot's head is in its neutral position. Theoretically, one could define the default camera orientation such that the ownship is in the center of the view if the pilot's head is orientated straight and level. In the depicted case, the camera would have been tilted downwards ($\theta_{cam,0} = \alpha_{cam}$); head rotations would be added to this pre-rotation. Even though this seems like a good choice at first, simulator tests revealed that such a setup becomes confusing in practice. Thus, it was not further evaluated.

7.1.2.3 Camera Frame of Reference

Figure 7.2 defined the camera position relative to a frame of reference with its origin at the ownship's reference point. This leaves the question of how the frame of reference should behave when the ownship yaws, pitches, or rolls: Should the whole system be aircraft-fixed and the camera rotate with the helicopter? Or should one or more axes stay aligned with the world-fixed frame of reference?

Obviously, the reference frame should be fixed to and rotate with the yaw angle of the helicopter. Otherwise, the exocentric view would change whenever the flight direction changes, which does not make sense. Regarding the remaining two rotation axes — pitch and roll — this decision is not as obvious.



(a) Pitch angle $\theta_{heli} = 0°$.

(b) Pitch angle $\theta_{heli} = 15°$.

Figure 7.3 – Camera frame coupled to ownship pitch rotation — This means the whole world (e.g. horizon, pad) changes within the view (own illustration).

Figure 7.3 illustrates one available option: an aircraft-fixed camera frame, rotating in sync with the ownship's pitch angle. As seen in the graphs, this implies that the tethered camera significantly changes its position and orientation with regard to the surrounding world. The resulting altitude change can be computed via

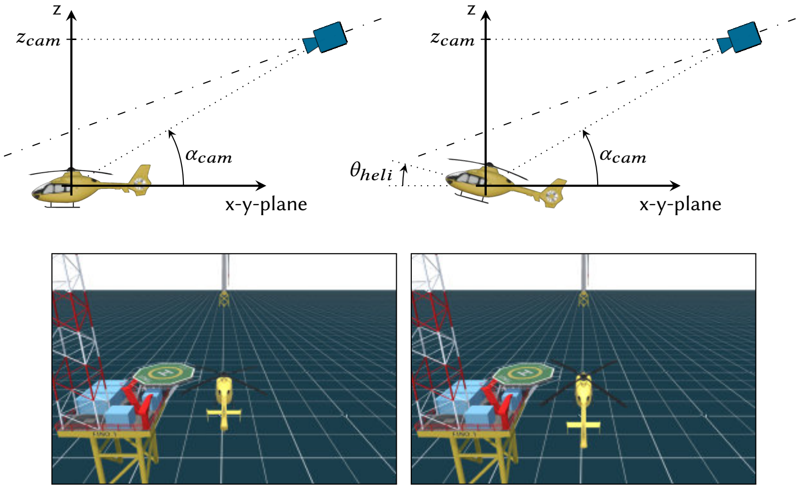
$$\Delta h_{cam} = d_{cam} \left[\sin\left(\alpha_{cam} - \theta_{heli}\right) - \sin\alpha_{cam}\right] \tag{7.1}$$

For the 15° pitch increase sketched in the figure, the camera moves 4.73 m downwards in the previously chosen setup ($\alpha_{cam} = 25°$, $d_{cam} = 19\,\text{m}$).

As a result, the whole view seen by the pilot changes. Comparing the screenshots in Fig. 7.3, one can see that the horizon is shifted downwards within the screen and all surrounding objects are seen from a flatter angle. On the positive side, this means that this variant provides strong visual cues for pitch angle changes. Even small variations are registered unconsciously through direct perception as nearly the whole view, including the salient horizon line, shifts. This is comparable to the pilot's usual cockpit sight where also the whole out-the-window view changes when the ownship attitude is altered. However, the introduced altitude change of the camera also generates confusing visual cues: It creates the impression that the ownship altitude is de-/increasing even though it is only the viewpoint that is moving.

The drawbacks of these viewpoint motions are avoided by the second variant, sketched in Fig. 7.4. Here, the camera reference frame is not coupled to θ_{heli}, which means that the x-y-plane remains parallel to the ground and the camera stays at the same height when the pitch angle changes. For the resulting view, this means that the horizon and all other surrounding objects remain at the same screen position for any pitch angle. This desired static viewpoint, however, comes with the downside that the only element that indicates pitch changes within the pilot's view is the attitude of the depicted helicopter itself (see screenshots in Fig. 7.4). This is of course not such a major visual cue as in the first variant where nearly the whole view is in motion when the pitch angle changes.

Regarding the roll angle, similar considerations were made but these are not detailed here. Taking all trade-offs into consideration, the author conducted practical comparisons in the simulator and finally decided to *not* couple the



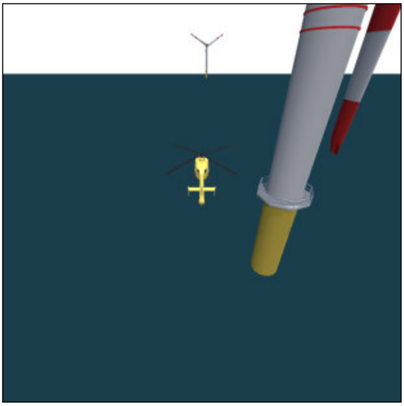
(a) Pitch angle $\theta_{heli} = 0°$. **(b)** Pitch angle $\theta_{heli} = 15°$.

Figure 7.4 – Camera frame aligned with world-fixed frame of reference — This means only the helicopter rotates, the world remains stable (own illustration).

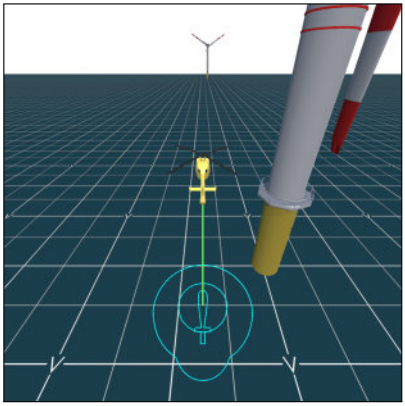
camera's reference frame to the ownship's pitch and roll rotations. Investigating the pilots' ability to sufficiently perceive the ownship attitude in such a setup, was one goal of the conducted study. Results and ideas for potential improvements are discussed in Sec. 7.4.

7.1.3 Integration of Scene-Linked & Conformal Symbology

3-D perspective views on a VR-HMD can replicate several depth cues that humans are used to from natural viewing. Monocular and binocular cues like occlusion, parallax, and relative size help the pilot to understand spatial relations and distances between objects (see Sec. 3.2.1.4 for details and references). However, the depth perception is only qualitative [206] and the pure perspective views come with the cost of LOS ambiguity [345], which impairs the perception of object locations. This problem exists in all perspective views including the egocentric cockpit view. In exocentric views, it is even greater because the location of both the ownship and the obstacle cannot be determined precisely.



(a) Without additional symbology the exact position of the helicopter can hardly be estimated correctly.



(b) A vertical dropline, a grid, and a visualization of the helicopter dimensions allow an exact position and distance perception.

Figure 7.5 – The value of conformal symbology in a tethered view (own figures).

To mitigate this issue, the author augmented the perspective views with synthetic depth cues, as recommended by previous research (see Sec. 2.4.2). Figure 7.5 shows how important this additional symbology is for the devised tethered view. Without conformal overlay, one can neither judge the exact position of the helicopter nor estimate its distance to the wind turbine tower. In the enhanced view, however, this is easily possible. The most important element is a so-called "dropline" pointing perpendicularly down from the helicopter. Thereby, it visually connects the ownship to its position over the ground. Together with the grid — which is part of the previously developed ocean surface symbology — this allows a *quantitative* comprehension of object positions and distances. To improve the judgment of obstacle clearances, a visualization of the helicopter dimensions plus a safety margin are integrated as outlines projected onto the ground. Optionally, these elements can also be drawn at the target hover height, which moves them closer into the pilot's viewing focus and provides an additional altitude cue.

7.1.4 Qualities & Limits of the Devised Tethered View

This section describes the benefits of a tethered view compared to the conventional cockpit perspective. Thereafter, several computations regarding the limitations of such a view are presented.

7.1.4.1 Advantages over the Conventional Cockpit View

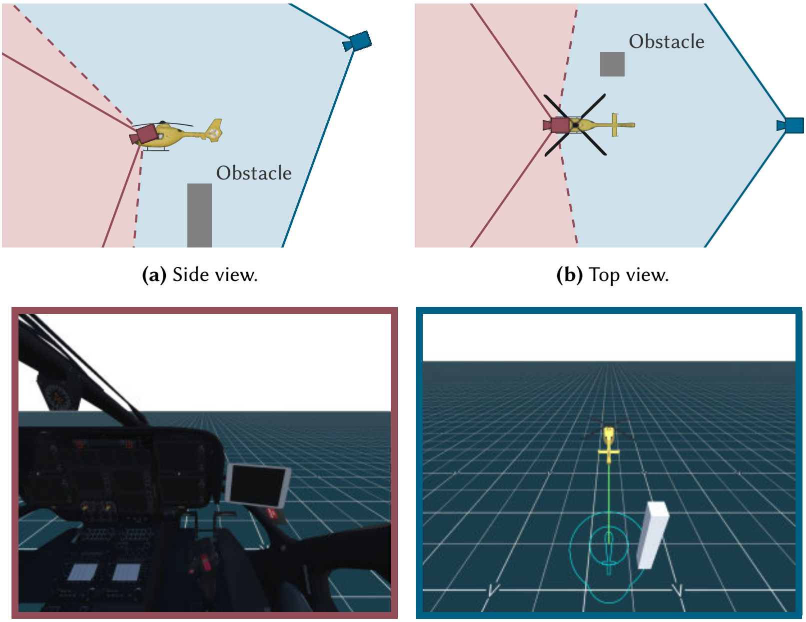
The general qualities of 3-D tethered views are well documented in the literature summarized in Sec. 2.4.2. Compared to 2-D co-planar displays, the pilot has a low cost of visual scanning and does not have to cognitively integrate information from various axes/planes into one 3-D mental picture of the situation. This is an important advantage over formats like the previously presented obstacle awareness symbology on the virtual instrument (Chapter 5). Further, the 3-D representations respect the principle of pictorial realism.

Additionally, the developed tethered view has two major benefits compared to the egocentric sight from the pilot's seat in a conventional cockpit. The exocentric viewpoint

- avoids a "keyhole view" [345] and generates a better overview of the ownship's surroundings,
- drastically reduces the masking of the outside vision by own aircraft structures.

These qualities appear to be a perfect match for DVE mitigation because they exactly address the two operation-specific DVE issues described in Fig. 1.1. More specifically, the adverse pilot eye point and the view-blocking aircraft structure were also identified as major challenges for pilots operating in offshore wind farms (see Sec. 3.4.3).

Figure 7.6 illustrates the two qualities. The FOV of both the ego- and the exocentric viewpoint are visualized by the blue and red areas in the side and the top view. Obviously, moving the camera to a position behind and above the helicopter results in a much wider area visible for the pilot. This has the enormous advantage that the pilot can now see obstacles aft below and on the side of the ownship. These would hardly be observable from the pilot's "keyhole view" in the cockpit. To some extent, the visible area of the cockpit view can be widened by turning the head. However, this is constrained by the pilot's head rotation limits — especially if the pilot has to control the helicopter simultaneously. Even if possible, it will not be as effortless as in the tethered view, which shows the whole near surroundings in the primary FOV with no head rotation required.



(a) Side view. **(b)** Top view.

(c) Cockpit view. **(d)** Tethered view.[7]

Figure 7.6 – Illustration of the superior viewpoint of a tethered VR-view —— in comparison with the sight from the cockpit (natural human visual field - - -, VR-HMD ——). The field of view (filled areas) of the former covers a significantly wider area around the ownship. This enables the pilot to see obstacles aft below and on the side, which cannot be seen from the cockpit viewpoint. Further, as seen in (c) and (d), the cockpit masks considerably more of the view than the helicopter fuselage in the tethered view (own illustration).

[7] Ownship and symbology appear very small in this screenshot. In VR, the image will be stretched across the HMD's 110-deg FOV, which enlarges the content significantly.

Additionally, because of the aircraft structure blocking the view, many areas cannot be seen even if the pilot looks in that direction. The drastic reduction of outside vision masking in the exocentric view is somewhat noticeable by comparing Figs. 7.6c and 7.6d. The cockpit structures cover a significantly larger portion of the view than the rather small helicopter representation in the tethered view. Not surprisingly, this problem increases substantially when looking in other directions where the ownship bottom and rear structures block nearly the whole outside vision.

7.1.4.2 Limitations of the Tethered View

In general, the most important limitation of tethered views is the LOS ambiguity. This cannot be avoided entirely, but at least it can be weakened by the developed conformal symbology (see Sec. 7.1.3). Beyond that general penalty, this section investigates specific limits of the devised tethered view by answering the following questions:

- What are the borders of the areas visible for the pilot?
- Within that, which areas are occluded by the ownship?
- In which cases do nearby objects restrict the pilot's view of the ownship and its immediate surroundings?

Borders of the Areas Visible for the Pilot As sketched in Figs. 7.2 and 7.6, the visible area is defined by the camera position, the camera orientation, and the GFOV. To figure out if an object — or more general a point of interest (POI) — can be seen by the pilot, one has to check if it is inside the resulting view frustum (additional occlusion checks see next paragraph). Each graphics engine does this implicitly when projecting the 3-D world onto the screen [2, Ch. 4]. To manually compute if a given POI is visible, one can follow the same steps:

1. Transform the POI position from world space (x, y, z) to camera space (x', y', z') via the so-called **view matrix**, which involves the camera

position $(x, y, z)_{cam}$ and orientation $(\psi, \theta, \varphi)_{cam}$:

$$\begin{pmatrix} x' \\ y' \\ z' \\ 1 \end{pmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\psi_{cam} & -\sin\psi_{cam} & 0 \\ 0 & \sin\psi_{cam} & \cos\psi_{cam} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_{cam} & 0 & \sin\theta_{cam} & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\theta_{cam} & 0 & \cos\theta_{cam} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdots$$

$$\cdots \begin{bmatrix} \cos\varphi_{cam} & -\sin\varphi_{cam} & 0 & 0 \\ \sin\varphi_{cam} & \cos\varphi_{cam} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} x - x_{cam} \\ y - y_{cam} \\ z - z_{cam} \\ 1 \end{pmatrix} \quad (7.2)$$

2. Perform the perspective projection, which further transforms the POI to homogeneous clip coordinates via the **projection matrix**:

$$\begin{pmatrix} x'' \\ y'' \\ z'' \\ w'' \end{pmatrix} = \begin{bmatrix} -\frac{f+n}{f-n} & 0 & 0 & -\frac{2fn}{f-n} \\ 0 & \frac{1}{\tan\frac{\Phi}{2}} & 0 & 0 \\ 0 & 0 & \frac{1}{\tan\frac{\Theta}{2}} & 0 \\ -1 & 0 & 0 & 0 \end{bmatrix} \begin{pmatrix} x' \\ y' \\ z' \\ 1 \end{pmatrix} \quad (7.3)$$

   where Φ, Θ are the horizontal and vertical GFOV and n, f represent the near and far clipping plane.

3. Divide the resulting homogeneous coordinates by w'' to receive Cartesian coordinates.

4. Check if the resulting coordinates are inside the unit cube (between −1 and +1 respectively), which means they are inside the view.

Considering only the FOV borders, not the clipping planes, simplifies the steps 2–4 to these checks:

$$|y'| \leq \left| x' \tan\frac{\Phi}{2} \right| \quad (7.4)$$

$$|z'| \leq \left| x' \tan\frac{\Theta}{2} \right| \quad (7.5)$$

With the presented formulas, one can answer many questions that are relevant for the implementation and the usage of a tethered view. For example:

- What is the outermost position for an object to be visible within the pilot's primary view?
- If outside the primary view, how far does the pilot have to rotate the head to make the object visible?
- In higher altitudes, how far down must the pilot tilt the head to see the dropline hitting the ground?

Occlusion by Nearby Objects To ensure a clear view of the helicopter and its close surroundings, one has to check if there are any sight-blocking objects between viewpoint and ownship. If this is the case, one can either adapt the camera position or — as it is a computer-generated view — render the view-blocking object (semi-)transparent.

Figure 7.7 shows a situation where an object near the landing spot occludes a certain space behind the helicopter. The masked area is determined by a ray from the camera through the upper edge of the object. The size of the visible safety zone is then defined by the point at which the ray hits the ground, i.e. the outermost point on the ground that is just visible. In the following, this will be referred to as POI.

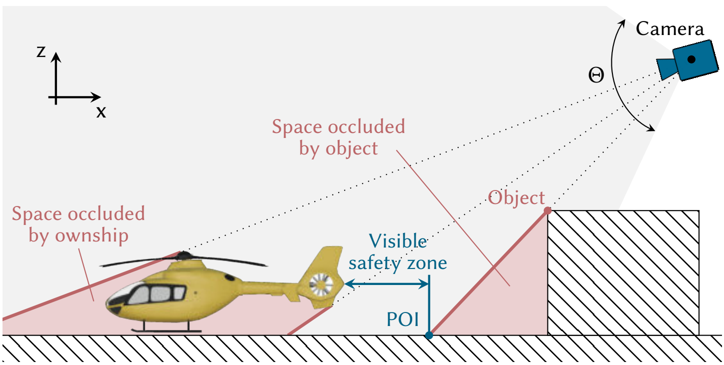


Figure 7.7 – Illustration of areas occluded by a nearby object and by the helicopter itself (own illustration).

The geometrical relation between the three points can be expressed with the intercept theorem:

$$\frac{x_{cam} - x_{poi}}{z_{cam} - z_{poi}} = \frac{x_{cam} - x_{obj}}{z_{cam} - z_{obj}} \tag{7.6}$$

If two of the three points are given, one can derive the minimal and maximal coordinates of the third point to make the POI just visible. In a generic way, the derived equations are:

$$x_{P_3} = x_{P_1} + \left(z_{P_3} - z_{P_1}\right) \frac{x_{P_1} - x_{P_2}}{z_{P_1} - z_{P_2}} \tag{7.7}$$

$$z_{P_3} = z_{P_1} + \left(x_{P_3} - x_{P_1}\right) \frac{z_{P_1} - z_{P_2}}{x_{P_1} - x_{P_2}} \tag{7.8}$$

where P_1, P_2, and P_3 can be any of the three points (Cam, Obj, and POI).

With these equations the following questions can be answered:

1. The obstacle position (x_{obj}, z_{obj}) and the viewpoint (x_{cam}, z_{cam}) are given. How large is the visible area behind the helicopter?

   - With z_{poi} set to the ground level:

$$x_{poi} = x_{cam} + \left(z_{poi} - z_{cam}\right) \frac{x_{cam} - x_{obj}}{z_{cam} - z_{obj}} \tag{7.9}$$

2. The obstacle position is given. How must the exocentric viewpoint be placed to get a safety zone of a certain size, i.e. to make the POI in the desired distance just visible?

   - What is the maximal horizontal position x_{cam} for a selected z_{cam}?

$$x_{cam} = x_{obj} + \left(z_{cam} - z_{obj}\right) \frac{x_{obj} - x_{poi}}{z_{obj} - z_{poi}} \tag{7.10}$$

   - Or vice versa, what is the minimal vertical position z_{cam} for a certain horizontal camera location x_{cam}?

$$z_{cam} = z_{obj} + \left(x_{cam} - x_{obj}\right) \frac{z_{obj} - z_{poi}}{x_{obj} - x_{poi}} \tag{7.11}$$

3. For a given exocentric view setup (x_{cam}, z_{cam}), what is an allowed obstacle configuration?

- How far away must an obstacle with a certain height z_{obj} be to make the POI just visible?

$$x_{obj} = x_{cam} + \left(z_{obj} - z_{cam}\right) \frac{x_{cam} - x_{poi}}{z_{cam} - z_{poi}} \tag{7.12}$$

- Or inversely, what is the allowed maximum height of an obstacle z_{obj} if it is located at x_{obj}?

$$z_{obj} = z_{cam} + \left(x_{obj} - x_{cam}\right) \frac{z_{cam} - z_{poi}}{x_{cam} - x_{poi}} \tag{7.13}$$

Even though camera orientation and FOV are not part of these equations, they are of course implicitly involved as the pilot must also look in the appropriate direction to have the POI within the view (see Eqs. (7.2) and (7.3)). The simulator study presented in the following considers exactly the elaborated scenario: an offshore landing platform where the pilots have to land with an obstacle in the back. For its implementation, the stated formulas were applied.

Areas Occluded by the Ownship As sketched in Fig. 7.7, the fuselage masks a space below and in front of the ownship. With the chosen parameters ($\alpha_{cam} = 25°$, $\beta_{cam} = 0°$), the portion of the view occluded by the helicopter is rather small[8] (see [22] for a computation of the correlation between masked area and α_{cam}, β_{cam}). Nevertheless, it is not negligible because *what* is hidden is more important than the size of the covered area alone. Here, the occluded space is in front of the helicopter and hidden obstacles could be very close to the aircraft. Even though an object would probably be visible during the course of flight before it enters that blind spot, the risk of a collision exists nonetheless. To avoid this, the ownship can be drawn semi-transparent, such that the pilot can still perceive the aircraft's attitude but additionally spot otherwise hidden objects. This solution is evaluated in the following simulator study (see Fig. 7.9). Further, a multi-modal approach with a supplemental spatial audio system was developed [22, 76]. The work shows how the blind spots of the tethered view can be compensated by 3-D audio warnings.

[8] The area is smaller than it seems from the side view in Fig. 7.7 because the tail boom occludes only a minor space due to its small width.

7.1.5 Required Data Sources

Blocking the natural out-the-window view and completely replacing it with a computer-generated view, as proposed here, inevitably means that all relevant data about the environment must be provided by the sensor and database module. What is not sensed or pre-stored there, cannot be seen by the pilot wearing the VR-HMD. Section 3.3.4 already discussed the general requirements on the data sources for such fully virtual external views: Data must be reliable, up-to-date, high-resolution, accurate, provided with low latency, and available in all targeted atmospheric conditions. In Cross' taxonomy (Fig. 2.14) this is referred to as class 3 (DAL A) system with full reliance on sensor data and imagery.

On top of that, the developed 3-D perspective views have their specific data source requirements. The transparent cockpit wants to provide the pilots with an unblocked view of their surroundings in every direction they might look. As a consequence, the data acquisition system must cover this whole field of regard. In practice, this implies that the common single forward-looking sensor will not be enough. Instead, a distributed aperture system with sensors pointing in different directions will be required. Using 2-D imaging sensors with different viewpoints means that parallax issues must be considered. Promising 360-deg near-field sensor systems and the Elbit Brightnite wide-angle sensor array were presented in Sec. 2.2.6.1 and 3.3.4.

Even higher are the demands for the tethered view with its exocentric viewpoint. The view includes the whole surroundings of the ownship. For certain viewpoints a 2.5-D reconstruction from sensor images may be enough. A 3-D model of the scene is needed to be able to freely position the viewpoint. This requires a 3-D capable data acquisition system that covers the whole 360-deg near-field. A possible solution could fuse data from sensors mounted all around the aircraft. Moreover, the so-called "see-and-remember"[9] strategy could be used to capture the scene during the approach phase or during a potential flyover before the actual DVE maneuver. Of course, this only works if no persistent DVE like fog is present and if no dynamic obstacles occur after the respective area was scanned. Finally, one could consider transferring data

[9] "See-and-remember" is a common strategy for brownout landings with lidar. The desired landing zone is scanned during the approach before the dust cloud builds up. Thus, the scene model exists prior to the actual landing, in which the sensor is not able to adequately penetrate the obscurants anymore [186].

from sensors positioned in the environment (e.g. a lidar sensor at the desired hover or landing spot) or mounted on escorting unmanned aerial vehicles (UAVs). The U. S. Army's ICE shows how a scene model can be generated from various inputs (see Fig. 2.20).

7.2 Evaluation Method

Three main pilot tasks were identified for confined area operations at the beginning of this chapter: 1) control, 2) guidance, and 3) conflict detection. The preceding section described how the author used the existing knowledge on 3-D perspective views to develop two virtual cockpit solutions with non-conventional view formats. To determine how well the developed views support the pilot in fulfilling the stated tasks, the author conducted the simulator study described in this section.

7.2.1 Research Questions

Both the transparent cockpit view and the tethered view were developed to improve the performance of task 2 and 3 without sacrificing the elementary task 1. To evaluate whether this goal could be reached, the presented pilot-in-the-loop experiment explored the following main questions:

- Do the developed 3-D perspective VR-HMD views improve the pilots' perception of the environment and support their spatial awareness in confined areas?
- Do the novel variants reach the good helicopter control & stabilization performance of a conventional cockpit view?

Subordinate questions were:

- Does the developed scene-linked and conformal symbology support the pilot and mitigate the LOS ambiguity?
- Can the spatial awareness be improved by rendering the aircraft structures semi-transparent?
- Does a semi-transparent fuselage have a negative influence on attitude perception?

- Are the few visual cues for attitude perception in the tethered view (Sec. 7.1.2.3) sufficient to manually control the helicopter?
- Can the larger viewing space of the tethered view (Sec. 7.1.4.1) reduce the pilots' head rotations and thereby simplify the helicopter control task and diminish potential workload and fatigue?

7.2.2 Participants

Eight male subjects with a mean age of 39 (min: 32, max: 49) participated in the experiment. All subjects either held a helicopter license (1 ATPL, 2 CPL, 1 PPL) or held a fixed-wing license and had extensive experience with DLR's helicopter simulator and its highly augmented FCS. The mean flight experience was 941 h (range: 200 h to 3100 h). Six participants used VR goggles before and three subjects had a mean in-flight experience of 30 h with HMDs. All subjects had normal or corrected to normal vision.

7.2.3 Apparatus

The experiment was conducted with the XR-Sim introduced in Chapter 4. For this study, configuration mode V was used (see Tab. 4.3). As illustrated in Fig. 7.8, this means that the pilot wore a non-see-through VR-HMD while sitting in a conventional cockpit. Detailed specifications of the used HMD — the Oculus Rift CV 1 — are given in Sec. 4.2.4 and Tab. 4.2. The experiment took place in DLR's GECO simulator. However, its outside vision projection and cockpit instruments were switched off because the participant was fully immersed in the virtual environment during the whole testing. Thus, as a side note, the same test conditions could have been realized without the GECO in the standalone XR-Sim setup (mode VI).

The flight simulation was provided by DLR's in-house helicopter model with modern FCS. This command model provides several command types and different levels of automation for the four control axes, which are explained in detail by Sec. 4.2.2. For this experiment, both cyclic axes were in *attitude command, attitude hold* mode, the collective was in *vertical velocity command, height hold*, and the pedals were in *rate command, direction hold*. This means

Figure 7.8 – Experimental setup with a pilot wearing the Oculus Rift CV 1 VR-HMD in DLR's GECO simulator.

that the control axes were mostly uncoupled; without disturbances, the helicopter remained in straight and level flight if the controls were in a neutral position. To increase the workload, the simulation included gusty wind which was not compensated by the FCS. The simulated wind consisted of a constant 15 knots head-wind combined with gust components, which permanently varied between ±5 knots in wind direction and ±2.5 knots in crosswind direction. By doing so, the pilots were forced to continually monitor their aircraft state and react accordingly.

In summary, the selected FCS modes simplified the flying task. It was chosen to place the focus on the spatial perception task with different viewing conditions. Nevertheless, because of the intentionally uncompensated wind disturbances, the setup still required permanent attention and control inputs to compensate for the ever-changing drift of the helicopter.

7.2.4 Tested 3-D Perspective Views

The study compared the developed 3-D perspective views and a conventional cockpit view. To do so, the experiment involved four display conditions called *Cockpit-Base*, *Cockpit-Trans*, *Exocentric-Base*, and *Exocentric-Trans*. As shown in Fig. 7.9, *Cockpit-Base* replicated a conventional cockpit on the VR goggles and served as a baseline for the experiment. *Cockpit-Trans* represented the transparent egocentric view introduced in Sec. 7.1.1. *Exocentric-Base* and *Exocentric-Trans* featured the tethered view developed in Sec. 7.1.2. Both exocentric variants were configured identically: $\alpha_{cam} = 25°$, $\beta_{cam} = 0°$, $d_{cam} = 19$ m, and yaw-only coupled camera frame. The only difference between the exocentric setups was the helicopter being transparent in *Exocentric-Trans*, which avoided the occlusions discussed in Sec. 7.1.4.2.

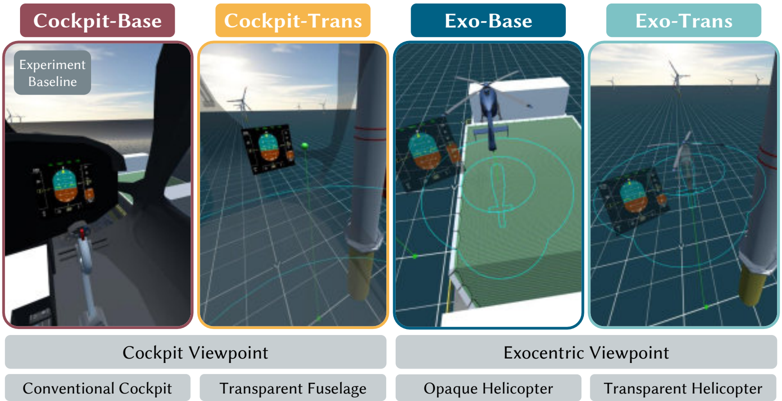


Figure 7.9 – The four tested perspective views captured during different phases of the hover and landing scenario. *Cockpit-Trans*, *Exocentric-Base*, and *Exocentric-Trans* are enhanced by conformal symbology highlighting the target position, the ownship position over the ground, and the size of helicopter and safety margin [74, 77].

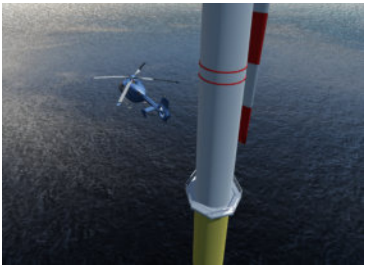
Each 3-D perspective view was equipped with a standard PFD. The exocentric layouts integrated it as a virtual, semi-transparent instrument on the lower left of the helicopter. In the cockpit views, it was located at its common place. *Cockpit-Base* as the experiment baseline had no additional assistance features. The other three views were enhanced with conformal symbology as introduced in Sec. 7.1.3. These view-augmenting elements can be seen in the screenshots in Fig. 7.9. The dropline below the ownship should be used to steer the aircraft to the desired hover position, which was marked by a green dot on the ground. To improve the estimation of obstacle distances, the helicopter outlines and a safety margin of half a rotor diameter were visualized by the blue lines. This symbology was projected onto the target hover or landing height. In addition to the described helicopter-fixed symbology, the desired hover point was highlighted by a green ball with a dropline (see screenshot of *Cockpit-Trans* in Fig. 7.9), which disappeared when the helicopter came closer than 7 m. Moreover, the ocean surface of the synthetic view was represented by the grid symbology developed in Chapter 6.

7.2.5 Task

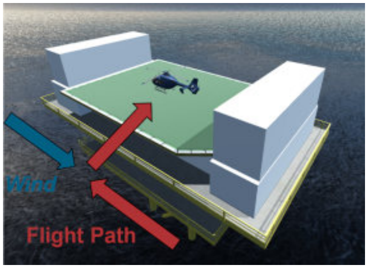
The display conditions were evaluated with two helicopter offshore scenarios: 1) a hover maneuver next to a wind turbine tower (Fig. 7.10a), and 2) a landing on an offshore platform between obstacles (Fig. 7.10b). Section 3.4.2 describes in detail how such tasks are performed by helicopter crews operating in offshore wind farms. They are a good choice for the assessment of the novel view types because they perfectly show the operational DVE issues of a conventional cockpit view when operating close to objects that are located on the side, below, or behind the ownship.

Hovering Next to a Wind Turbine Tower The hover maneuver next to the wind turbine tower was basically the same scenario that was already used for the evaluation of the VCIs in Chapter 5. In this experiment, the participants flew a straight approach starting 0.25 NM out and 250 ft above the target hover position. The initial airspeed was 40 knots with 15 knots headwind. As previously detailed in Fig. 3.19, the pilot had to steer the helicopter to a position abeam the tower. The pilots were instructed to acknowledge when in the desired position by pushing a button on the cyclic stick. This started a 2 min hover phase in which the subjects should hold the desired position as precisely as possible. Two of the screenshots in Fig. 7.9 show this maneuver while approaching the wind turbine (*Cockpit-Trans*) and during the hover phase (*Exocentric-Trans*).

Landing on an Offshore Platform Between Obstacles The second task was a confined area landing on an offshore platform. The approach phase was similar to the hover task: straight towards the wind, 0.25 NM out, and 250 ft above the helipad with an initial airspeed of 40 knots. The whole maneuver had to be conducted with head-wind. As the direct approach path was blocked by an obstacle on the platform (see Fig. 7.10b), the pilots had to approach a point on the left of the helipad and then hover sideways to the right to reach the desired landing spot. Figure 7.10b shows a helicopter with



(a) The helicopter in the desired hover position abeam the wind turbine tower.



(b) The helicopter in the desired landing position in the middle of the offshore platform.

Figure 7.10 – Illustration of the hover and the landing task [74].

the desired "headwind-heading" in its final position in the middle between the two obstructions. The width of the landing pad was 22.4 m, the clear space between the obstacles was 31.3 m. The screenshots of *Cockpit-Base* and *Exocentric-Base* in Fig. 7.9 show this maneuver from the pilot's perspective.

7.2.6 Experimental Design & Procedure

The experiment compared the four described display types using a within-subject design with counterbalanced conditions. As detailed above, the study comprised two separate tasks. Each maneuver was flown twice with the same display condition. This resulted in a total of 16 flights per participant: 4 displays × 2 tasks × 2 repetitions.

The experiment started with a briefing and a demographic questionnaire. During the following training session, the participant flew both mission tasks with all display conditions until he was familiar with the simulator and the symbology. After a first break, the actual testing phase was conducted in two blocks of eight flights. Each block lasted approximately 40 min and comprised all runs with the same viewpoint: either both cockpit views or both exocentric views. Within these viewpoint blocks, the two landings and two hover maneuvers with the same symbology were executed in a row. The blocks were separated by a 15 min break. Subjective feedback was gathered with the 3-D SART [302] after each condition and a tailor-made questionnaire during the final de-briefing. Additionally, the subjects completed the Simulator

Sickness Questionnaire [142] before the testing phase and after each display condition (i.e. every four flights). The total experiment duration was around three hours.

7.3 Evaluation Results

To answer the research questions stated in Sec. 7.2.1, this study considered the dependent measures listed in Tab. 7.1. The examination if the developed 3-D perspective views can improve spatial awareness is based on the pilots' subjective feedback as well as on the objective measurements of landing performance and hover accuracy. The contribution of the devised conformal symbology to this is assessed with a questionnaire. Further, the pilots' perception of the ownship attitude is investigated via control behavior and pilot comments. Finally, a look at the recorded head motion data reveals if the superior viewpoint of the tethered view can reduce the required head rotations.

Table 7.1 – Overview of the dependent measures used in study IV.

Research Question	Indicators	Measures*
Spatial awareness	Hover accuracy	Target position capture Flight path
	Landing performance	Touchdown position Obstacle clearance
	Pilot feedback	DBQ, 3-D SART
Value of conf. symbology	Pilot feedback	DBQ
Attitude perception	Control behavior Pilot feedback	Pitch angle distribution DBQ
Head rotation behavior	Head motion patterns	Head angle distribution Angular distance covered

* DBQ = debriefing questionnaire, 3-D SART = three-dimensional situation awareness rating technique [302].

The recorded aircraft state, flight path, and head-tracking data as well as the questionnaire results were preprocessed and analyzed with MATLAB [182] and the statistical computing environment R [249]. This section presents a subset of the data, condensed to the most important findings. An α level of .05 was adopted for statistical significance.

7.3.1 Spatial Awareness

The tested 3-D perspective views were developed to improve the pilots' perception of the surroundings in confined area operations. This section analyzes if the displays really could improve their spatial awareness.

7.3.1.1 Flight Performance — Hover Task

Position at the Start of the Hover Maneuver The first part of the hover task was to find the desired hover location and acknowledge "on position". Figure 7.11 shows the distance between the actual target point and the position chosen by the pilots. This reflects how precise the pilots could estimate their spatial location with the tested view. A repeated-measures ANOVA revealed that the position deviation was significantly affected by the display variant, $F(3, 21) = 8.553$, $p = .018$, $\eta^2 = .429$. The boxplots show disadvantages for *Cockpit-Base* compared to the other display conditions. This effect was confirmed by Tukey post hoc tests ($p < .001$ for all three comparisons).

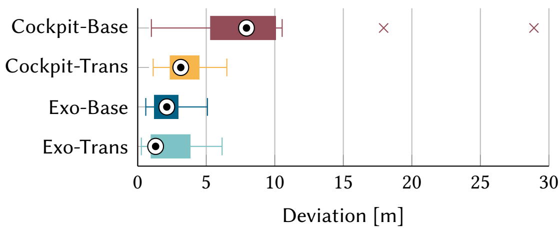


Figure 7.11 – Position deviation from desired hover point at the start of the hover maneuver [68, 77].[10]

[10] Boxplots show median (dot/circle), 25th and 75th percentiles (filled rectangle), and outliers (x markers) with whisker length 1.5 interquartile range.

Flight Path during the Hover Maneuver Thereafter, it is interesting how well the pilots could hold the desired position during the 2 min hover phase. The differences between the display conditions are illustrated in Fig. 7.12, which shows top views of all flight paths. The area covered while using the exocentric perspectives appears to be smaller than with the cockpit views. Moreover, the flight paths of the former are nearly centered around the target spot while the pilots tend to have the target on a 1 or 2 o'clock position when in cockpit view.

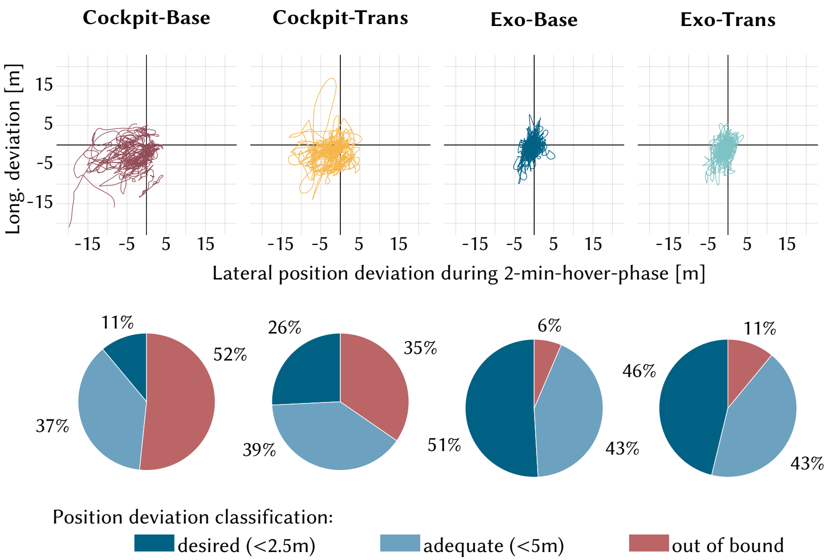


Figure 7.12 – Position deviation during the 2 min hover phase — Top: Top view of all flight paths. Bottom: Pie charts showing percentages of the total hover time within three position accuracy classes [68, 77].

For further evaluation, the position deviations recorded over the 2 min hover phase were classified: Deviations smaller than 2.5 m are categorized as "desired", differences up to 5 m correspond to "adequate". The pie charts in Fig. 7.12 indicate that pilots sitting in the conventional VR cockpit stayed outside the "adequate" 5 m radius more than half of the time. In only 11 % of the time, they were within the "desired" range. This performance is improved with *Cockpit-Trans* but the participants still hovered one-third of the time "out of bound”. With both exocentric perspective views, the helicopter was within the “desired” and “adequate” limits around 90 % of the total hover time. A repeated-measures ANOVA confirmed that the type of perspective view has a significant effect on the hover duration in the “desired” zone, $F(3, 21) = 11.490$, $p < .001$, $\eta^2 = .475$. As shown in Tab. 7.2, Tukey post hoc tests revealed that both exocentric viewpoint variants performed significantly better than the cockpit views.

Table 7.2 – Post hoc comparison of the perspective views regarding hover duration in the “desired” zone. A star (*) indicates statistically significant differences [77].

Comparison			p	
Cockpit-Base	–	Cockpit-Trans	.175	
Cockpit-Base	–	Exo-Base	< .001	*
Cockpit-Base	–	Exo-Trans	< .001	*
Cockpit-Trans	–	Exo-Base	.003	*
Cockpit-Trans	–	Exo-Trans	.024	*
Exo-Base	–	Exo-Trans	.915	

7.3.1.2 Flight Performance — Landing Task

In the landing scenario, the pilots were instructed to approach an offshore platform from the left side and land the aircraft sideways between two obstacles. The task was to leave sufficient obstacle clearance during the whole maneuver and to touch down in the middle of the platform.

Touchdown Position Figure 7.13 shows top views of the touchdown positions achieved with the four display conditions. The comparison reveals that the lateral position deviation was higher with *Cockpit-Base* (median: 1.3 m) compared to *Cockpit-Trans* (median: 0.8 m), *Exocentric-Base* (median: 0.4 m), and *Exocentric-Trans* (median: 0.5 m). Furthermore, the measured deviations are spread wider with the cockpit variants. The median longitudinal deviations were — within every condition — larger than the corresponding lateral offsets. They range from 1.3 m (*Exocentric-Trans*) via 1.2 m (*Cockpit-Base*) and 1.0 m (*Cockpit-Trans*) to 0.8 m (*Exocentric-Base*). Also, the values of *Cockpit-Base* are widely spread and the exocentric views seem to have a tendency to a touchdown position slightly ahead of the desired position. A repeated-measures ANOVA found a significant effect of the display condition on the lateral deviation only, $F(3, 21) = 5.663$, $p = .005$, $\eta^2 = .301$. The post hoc tests confirmed that *Cockpit-Base* performed worse than *Exocentric-Base* ($p < .001$) and *Exocentric-Trans* ($p = .008$). All other comparisons were not significant.

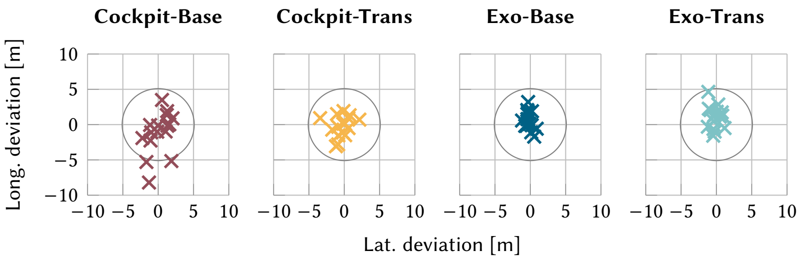


Figure 7.13 – Top views of the touchdown positions obtained with the four display variants. The graphs show lateral and longitudinal deviations from the desired landing spot in the middle of the platform [74].

Obstacle Clearance A repeated-measures ANOVA found no significant effect of the display variant on the minimal obstacle experienced during the landing maneuver, $F(3, 21) = 1.658$, $p = .206$, $\eta^2 = .112$. To further evaluate how well the pilots maintained the required obstacle clearance, three classes were defined: "desired" refers to a distance to the nearest object of more than three-fourths of the rotor diameter (7.65 m); "adequate" covers smaller distances that are larger than half a rotor diameter (5.1 m); even smaller clearances are considered "below safety limits". Figure 7.14 shows for how long the obstacle clearance was within each of these zones (measured in percentage of the total landing duration). As expected, the distance to the obstacles was as "desired" or at least "adequate" most of the time for all view types. However, the pilots in the conventional cockpit operated below the safety limits in 8% of the time. With *Cockpit-Trans* and *Exocentric-Trans* this portion was 4%. Only with *Exocentric-Base* the time share below the safety limits was less than 1%.

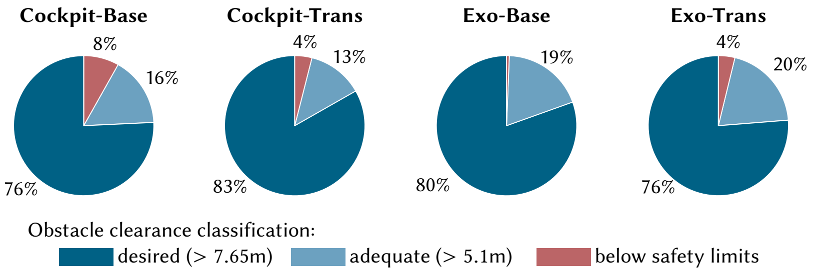


Figure 7.14 – Obstacle clearance during the landing phase: Pie charts show how long the aircraft was within the defined obstacle clearance zones, in percentages of the total landing duration [74].

7.3.1.3 Pilot Feedback

Cockpit vs. Tethered View The debriefing questionnaire and pilot comments confirm the advantages of the exocentric viewpoint. Figure 7.15 shows that the tethered views were reported to improve spatial orientation and collision avoidance creating a feeling of safety. In detail, the pilots stated that they "could easily judge the distance to obstacles in the back of their helicopter" from an exocentric viewpoint, whereas this appears to be nearly impossible from inside the cockpit regardless of helicopter fuselage transparency. The cockpit variants were rated better for estimating the distance to obstacles in front and on the side but still not as good as their exocentric counterparts. Further, a slight advantage could be seen for the transparent compared to the conventional cockpit view. Despite that, the results cannot clarify whether the exocentric perspectives reduced workload. However, an increase in workload was not reported either.

3-D SART The mean total scores of the 3-D SART questionnaire [302] were 83.75 for *Cockpit-Base*, 88.75 for *Cockpit-Trans*, 96.88 for *Exocentric-Base*, and 103.13 for *Exocentric-Trans* (averaged over the whole experiment). A significant effect of the display type on the 3-D SART total score was found by a repeated-measures ANOVA for the hover task, $F(3, 21) = 4.805$, $p = .011$, $\eta^2 = .159$. Tukey post hoc tests revealed that the scores of *Cockpit-Base* were significantly lower than the values obtained for *Exocentric-Base* ($p = .003$) and *Exocentric-Trans* ($p = .007$). All other comparisons were not significant.

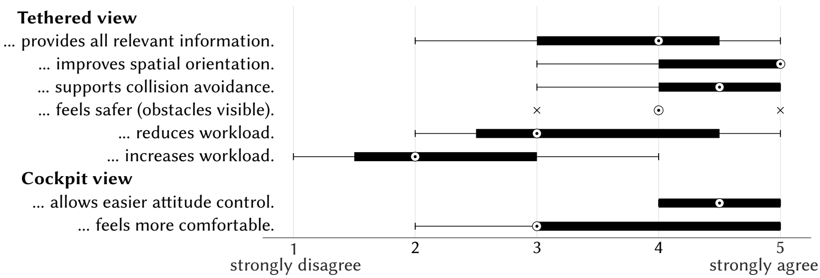


Figure 7.15 – Subjective comparison of cockpit and tethered view [77].[10]

7.3.2 Rating of the Conformal Symbology

Figure 7.16 illustrates the rating of the conformal symbology, which was available in all display conditions but the conventional cockpit view *Cockpit-Base*. The conformal overlay was rated very positive for the exocentric perspective views. Both the safety margin circle and the green target balls were clearly rated to be useful. The projection of the target point on the ground together with the vertical green line appeared to be of major help in the exocentric view conditions. However, in the cockpit view, the symbology appeared to have flaws. For instance, the vertical green dropline was hardly usable in *Cockpit-Trans* since the pilots had to tilt their heads far down to see the line and the target dot under the aircraft. Further, the last statement of the survey indicates unnecessary complexity and confusion.

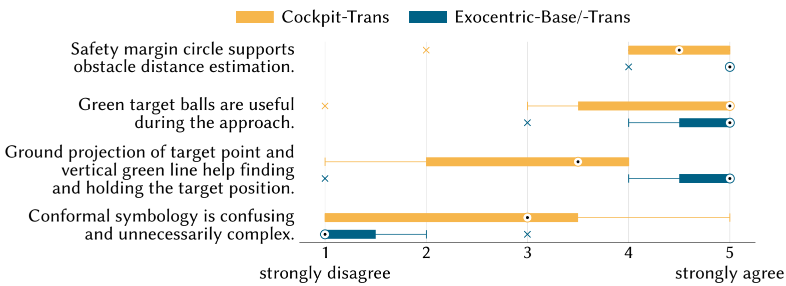


Figure 7.16 – Rating of the conformal symbology introduced in Sec. 7.1.3 and Sec. 7.2.4 [68].[10]

7.3.3 Helicopter Attitude Perception and Control

A key question of the study was if the pilots are able to control the helicopter from a viewpoint outside of the cockpit. Most importantly, the experiment confirmed that all pilots could perform their tasks with the developed tethered views. Nevertheless, the participants also reported that controlling the attitude of the helicopter appeared to be easier when sitting inside the cockpit (see Fig. 7.15). Further, a few pilots stated that they had to use the PFD more often to assess the attitude when flying with the exocentric viewpoint.

The issue was further explored by comparing the distributions of the pitch angles measured for each of the four view types. Figure 7.17 depicts boxplots, which are based on eight pitch measurements per second (960 values per run). The graphs reveal that the distribution width for *Cockpit-Base* is smaller than for all non-conventional display conditions. Especially the boxplot of *Exocentric-Trans* has a wider interquartile range and outliers ranging from $-20°$ to $28°$. In summary, the boxplots show that the pilots commanded more extreme pitch angles with the transparent cockpit and both exocentric views. Nevertheless, it has to be noted that these large values occurred rarely and differences of the middle 50% of the data (i.e. the boxes) are small.

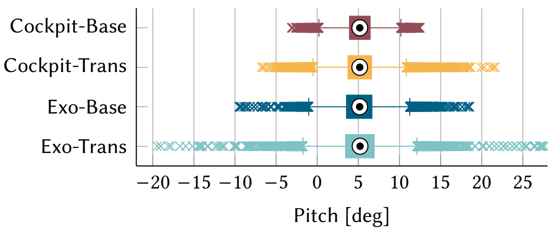


Figure 7.17 – Distribution of recorded pitch angles during the hover task [68, 74, 77].[10]

7.3.4 Head Rotation Behavior

As described in Sec. 7.1.4.1, the tethered views provide the pilots with a larger viewing space around the ownship and make objects below, behind, and on

[10] Boxplots show median (dot/circle), 25th and 75th percentiles (filled rectangle), and outliers (x markers) with whisker length 1.5 interquartile range.

the side visible inside the primary FOV. Since continual head motion can increase workload, lead to fatigue, and complicate the helicopter control task, it is interesting to investigate how the tested display conditions affected the pilots' head rotation behavior.

7.3.4.1 Hover Task

Typical Head Motion Patterns Figure 7.18 depicts a typical head rotation pattern of a participant performing the hover task with *Cockpit-Base*. The upper curve shows that the pilot turned his head about 40° – 60° to the right towards the wind turbine tower. Moreover, he switched his view to the forward direction with fast and regular movements. During the whole hover maneuver, the head pitch angle remained within 0° and −20°. Apparently, the pilot tilted his head slightly downwards when he looked in the longitudinal direction of the aircraft. With *Cockpit-Trans* the head motion behavior looked similar in many cases. However, some participants also regularly tilted their heads downwards more than 50° so as to check the position deviation via dropline and target dot symbology located under the aircraft.

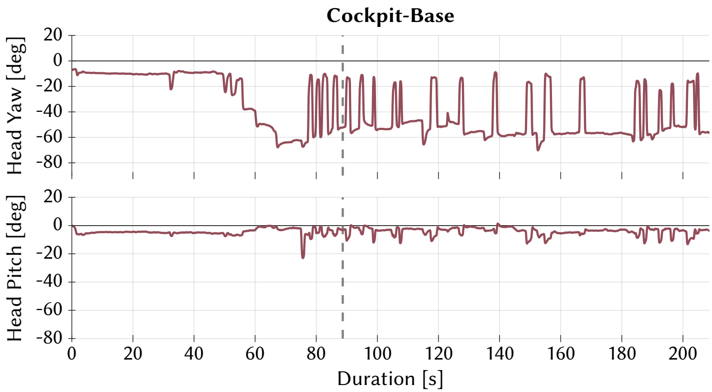


Figure 7.18 – Typical[11] head motion during the hover task with *Cockpit-Base*. The dashed line indicates the start of the 2 min-hover-phase. Negative yaw values correspond to viewing directions to the right where the wind turbine tower was located [74].

[11] Data from one pilot which is representative of the majority of the recorded data.

Both exocentric variants led to entirely different head motion curves. As shown by Fig. 7.19, the typical head yaw and pitch curves show few movements during the approach phase and almost no head motion during the hover phase. The pilot continuously looked in forward direction with his head tilted 40° down. The negative pitch can be explained by the ownship and the hover position symbology being located below the viewpoint ($\alpha_{cam} = 25°$).

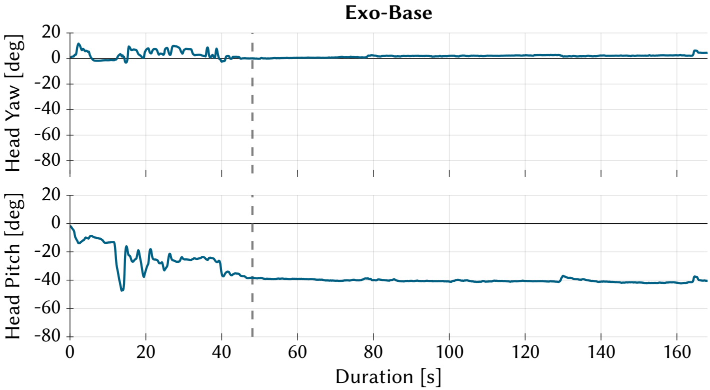


Figure 7.19 – Typical head motion during the hover task with *Exocentric-Base*. The dashed line indicates the start of the 2 min-hover-phase. Negative pitch values indicate a downwards head tilt towards ownship and hover symbology [74].

Yaw & Pitch Angle Distribution The observations from the individual head movement curves can be confirmed for all participants by comparing the overall distribution of the recorded head yaw data. The histogram plots in Fig. 7.20 show that the pilots never turned their heads more than 20° left or right in the exocentric conditions. In contrast, the head yaw was over 50° rightwards in 80% of the hover time with *Cockpit-Base*. *Cockpit-Trans* could reduce this amount to 61%.

Regarding the pitch rotation, both exocentric views caused the pilots to tilt their heads downwards between −20° and −50° in 85% of the time. In contrast, when the pilots flew with the cockpit views, their head pitch was within ±20° in 89% (*Cockpit-Base*) and 76% (*Cockpit-Trans*) of the hover time. *Cockpit-Trans* was the only display variant where head pitch angles smaller than −50° were observed (7%). This can be explained by the pilots using the dropline and the target dot under the aircraft for position holding.

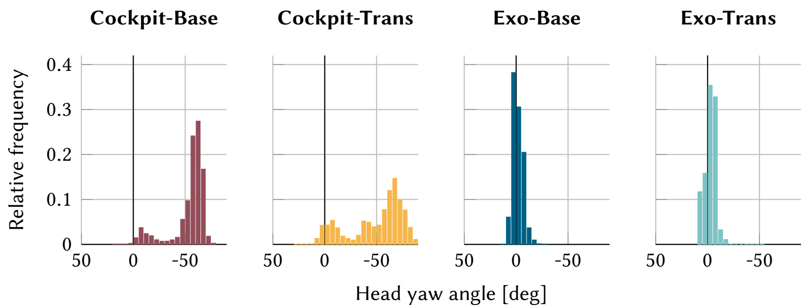


Figure 7.20 – Distribution of the pilots' head yaw rotation φ during the hover maneuver. Negative values correspond to viewing directions to the right where the wind turbine tower was located.

Angular Distance Covered Besides the amount of time spent in the respective head yaw zones, the actual head movement is another important criterion. To investigate that, the total angular distance covered through head rotations during the hover phase was computed per flight. Table 7.3 shows the median of these values for each display condition. The data confirms Figs. 7.18 and 7.19: In yaw direction, the angular distance was significantly higher for the cockpit variants (ANOVA: $F(1.36, 9.55) = 11.990$, $p = .004$, $\eta^2 = .468$ (Greenhouse-Geisser corrected); post hoc tests: *Cockpit-Base* – *Exocentric-Base/-Trans*: $p = .002$, *Cockpit-Trans* – *Exocentric-Base/-Trans*: $p < .001$). Regarding the head pitch direction, the numbers are closer together. Nevertheless, the differences were still found to be significant by a repeated-measures ANOVA, $F(1.39, 9.72) = 5.882$, $p = .029$, $\eta^2 = .386$ (Greenhouse-Geisser corrected). The post hoc tests revealed that only *Cockpit-Trans* induced significantly longer head movements in pitch direction compared to *Exocentric-Base* ($p < .001$) and *Exocentric-Trans* ($p = .001$).

7.3.4.2 Landing Task

Typical Head Motion Patterns During the landing task, partly similar head motion behavior was observed. Nevertheless, due to the different task characteristics, the rotations were not as extensive as during the hover task. Again, with *Cockpit-Base* the pilots quickly turned their head between forward

Table 7.3 – Angular distance covered by head rotations during the hover task.

	Angular Distance Covered [a]	
	Yaw	Pitch
Cockpit-Base	996°	291°
Cockpit-Trans	1430°	485°
Exocentric-Base	99°	150°
Exocentric-Trans	117°	209°

[a] median of head rotation data from all flights.

and rightward direction in order to land the helicopter sideways between the obstacles. Typically, *Cockpit-Trans* caused large downward tilts when the participants used the dropline to judge their position over the ground. Similar to the hover task, both exocentric views required no fast LOS changes.

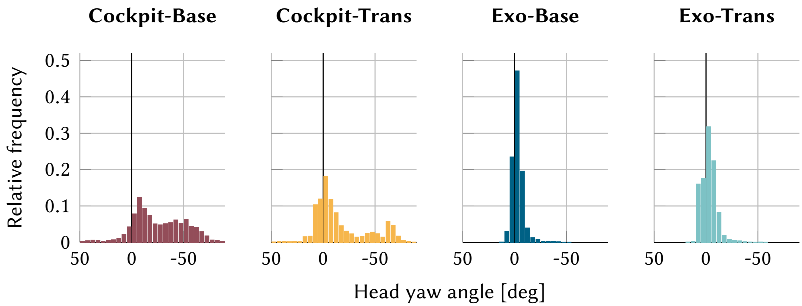


Figure 7.21 – Distribution of the pilots' head yaw rotation φ during the landing maneuver. Negative values correspond to viewing directions to the right where the landing pad was located.

Yaw & Pitch Angle Distribution Figure 7.21 shows that the yaw rotation was smaller than 20° in 98% of the time flying in the exocentric conditions. For the landing task, the histograms of *Cockpit-Base* and *Cockpit-Trans* have no peak around 60°. Instead, the recorded yaw angles are almost evenly spread between forward and rightward viewing direction for the conventional view. The transparent cockpit even caused the pilots to look in forward direction about two-thirds of the time. Still, both cockpit views provoked yaw rotations larger than 50° in about 20% of the landing duration. The pitch rotation distribution was comparable to the values observed during the hover task. Only *Cockpit-Trans* caused head tilts higher than 50° downwards (4%). With the exocentric viewpoints, the pilots tilted their heads down by 20° to 50° for 80% of the landing duration. By contrast, with the conventional view *Cockpit-Base* the vertical LOS direction was within ±20° for the same amount of time. With the transparent cockpit this value was reduced to 55%.

Angular Distance Covered The median angular distance that the pilots covered by turning their heads in yaw direction was highest with *Cockpit-Base* (879°), followed by *Cockpit-Trans* (742°). Similar to the hover task, significantly lower head turn medians of 84° and 110° were measured for *Exocentric-Base* and *Exocentric-Trans* (ANOVA: $F(1.64, 11.45) = 14.440$, $p = .001$, $\eta^2 = .497$ (Greenhouse-Geisser corrected); post hoc tests confirmed differences between all cockpit and exocentric variants respectively ($p < .001$)). The angular distances in pitch direction were 282° for *Cockpit-Trans*, 123° for *Cockpit-Base*, 110° for *Exocentric-Trans*, and 71° for *Exocentric-Base*. Again, a significant effect of the display condition was found by a repeated-measures ANOVA, $F(3, 21) = 4.843$, $p = .010$, $\eta^2 = .190$. As for the hover task, the post hoc tests confirmed significantly longer head pitch movements in *Cockpit-Trans* compared to *Exocentric-Base* ($p = .003$) and *Exocentric-Trans* ($p = .002$).

7.4 Discussion

In answer to the two main research questions stated in Sec. 7.2.1, it can be concluded that the developed tethered views improved the pilots' perception of the environment and supported their spatial awareness in the examined confined area maneuvers. Moreover, stabilization and control of the helicopter appeared to be generally possible from an exocentric viewpoint with the used attitude command FCS. Nevertheless, the author suggests further investigating the pilots' ability to judge and control helicopter attitude with the non-conventional views. Additional findings, remaining questions, and ideas for improvement are discussed in the following.

7.4.1 Evaluation Results

Spatial Awareness with Tethered View Regarding spatial awareness, the experiment delivers a clear picture: The developed tethered views have significant advantages over the conventional cockpit view on VR goggles. In the simulated hover scenario, the pilots could find and hold the desired hover point more precisely. During the landing maneuver, the flight performance differences were not as large as during the hover task but still visible. In total, *Exocentric-Base* performed best as it caused the smallest deviations from the desired touchdown position and also improved the obstacle clearance. These objective flight data results are confirmed by the 3-D SART, the debriefing questionnaire, and pilot comments. The findings are in line with Wickens [345], who states that an "exocentric 3-D display is often considered superior for many situation awareness tasks" because the small FOV of the egocentric perspective hides critically important features and creates a "keyhole effect".

As a side note, the position deviations during hover were relatively large for all display conditions. This was due to the challenging wind conditions, which were intentionally chosen to better see the differences in pilot behavior and performance. Further, this maneuver is usually not flown alone but with assistance from a hoist operator in the back of the helicopter [79].

Spatial Awareness with Transparent Cockpit The transparent cockpit view was clearly outperformed by the exocentric viewpoint. However, the study still found spatial awareness advantages over the conventional cockpit view. Being able to look through the aircraft structures clearly improved the pilots' ability to find the target hover point. However, during the 2 min hover phase, the subjects could not hold this position as precisely as with both exocentric display conditions. Even though the conformal symbology showed the desired obstacle distance, most participants could not fully translate this auxiliary information to better performance. In the author's opinion, this is — similar to *Cockpit-Base* — mainly caused by the fact that it requires much effort and continual LOS changes to visually gather all required information: the wind turbine at the right, the PFD on the dashboard straight ahead, and the dropline and target dot below. In contrast, the exocentric views present an overview of the whole situation with all information available within a small area of the forward FOV. This emphasizes the author's argument that not only the view-blocking structures but also the pilot's eye point is a crucial operational DVE issue. Additionally, judging lateral positions and distances from a viewpoint behind the aircraft is obviously easier than from an egocentric view in LOS direction.

Conformal Symbology The overlaid dropline and safety margin symbology clearly mitigated the LOS ambiguity problems of the 3-D perspective views. It remains for future research to investigate if the somewhat compelling nature of this symbology may cause attention fixation issues.

Head Rotation Behavior The study revealed that the larger viewing space of the tethered view significantly reduces the pilots' head rotations during maneuvers in confined areas with obstacles on the side and behind the ownship. When sitting inside the cockpit, the tested maneuvers caused the pilots to have their heads turned to the right for a significant amount of time. Furthermore, many fast LOS switches were observed between the forward and the rightward direction, where wind turbine tower or landing pad were located. With the exocentric perspective, the participants did not have to turn their heads. As expected, they just kept their heads tilted slightly downwards to have the helicopter and the dropline in sight. Of course, these phenomena are highly task-dependent. In this study, they were more pronounced in the hover scenario than in the landing task.

As can be seen from Fig. 7.12, several participants tried to avoid extensive head turns by hovering left behind the target position. In doing so, they had the obstacle at 1 or 2 o'clock instead of the desired 3 o'clock position. Additionally, heading changes out of the wind, towards the wind turbine could be observed now and then. However, both strategies are not practical in an actual offshore hoist operation. Future research should investigate if an increased peripheral FOV in the egocentric perspective has a positive effect.

Fewer head movements and less strenuous head poses can simplify the helicopter control task and diminish workload and fatigue. Nevertheless, it is also important to note that head motion can also have positive effects on creating spatial awareness.

Helicopter Attitude Awareness A central research question was whether the few visual attitude perception cues in the tethered view are sufficient to manually control the helicopter. Further, the influence of a semi-transparent fuselage on attitude perception was unclear.

Overall, the pilots could control the helicopter and fulfill their task with every view format but indeed the study revealed a slight tendency to command larger pitch angles in all non-baseline view types. Additionally, both transparent variants had a wider pitch angle distribution than their respective non-transparent counterparts.

Missing or less striking visual cues for attitude perception can be an explanation for this observation. When sitting inside the cockpit, the relative motion of the external scene gives the pilot an instant impression of the helicopter attitude. The horizon moving within the FOV and relative to the instrument panel is even perceived via peripheral vision when the pilot is focusing on another task. The semi-transparent airframe of *Cockpit-Trans* makes many aircraft references less apparent, which may impede the pilot's attitude awareness. However, in contrast to the devised tethered view, the most important attitude cue — the horizon — is still usable. The evaluated exocentric viewpoint was world-aligned (cf. Sec. 7.1.2.3), which implies that the horizon was always horizontal and did not move vertically in the pilots' view when they altered the pitch or roll angle. Thus, the helicopter attitude could only be derived from the rotation of the helicopter model or the artificial horizon in the virtual PFD. Of course, both options are less striking and noticeable than the movement of the horizon spanning the whole FOV. This reasoning is supported by the participants reporting that the cockpit view allows for easier attitude control and that more frequent usage of the PFD was required for the tethered views.

An inferior explanation for the larger pitch amplitudes can be that even small position deviations are easily seen with the conformal symbology. As a consequence, the pilots might have tried to more rapidly correct their gust-induced drift with larger control inputs.

The attitude awareness issues agree with the prevalent notion that egocentric views are the better choice for manual control tasks. As more and more advanced FCS simplify the actual control task, one may raise the question of whether such a cockpit view will still be the optimal solution or if an exocentric viewpoint might induce an overall better performance for such semi-automated operations. Thus, the author recommends a follow-up investigation with a higher automation level to confirm this hypothesis. Further, the following section discusses several ideas on how one could improve the attitude perception in the developed views.

7.4.2 Open Questions & Potential Advancements

The observations and results of this first exploratory study raised several follow-up questions and generated ideas for potential advancements. Three concrete suggestions are discussed in the following. Recommendations concerning the virtual cockpit concept as a whole are described later in Sec. 8.3.

How can the attitude perception in the tethered view be improved?
Future work on tethered views could follow two distinct paths to improve the pilot's attitude awareness:

1. keep the view as it is and add/improve supplementary indicators that show the ownship attitude, or
2. adapt the view to provide better attitude cues by itself.

The tested tethered views already had a virtual standard PFD that provided the pilot with attitude information in a well-known format. However, it might have been confusing that this PFD showed its usual inside-out[12] view of the situation whereas the exocentric main view was an outside-in format with fixed real-world and only the aircraft rotating (see Sec. 7.1.2.3). To avoid this potential conflict, one could include an outside-in PFD. This way both the main view and the attitude indicator would follow the same principle: horizon fixed, aircraft moving.

An even more promising approach might be to remove the virtual 2-D PFD entirely and integrate the required information conformally into the main 3-D view. As the rotating ownship already is *the* natural attitude indicator, the author suggests adding a conformal pitch and roll scale and using the aircraft itself as the pointer. Comparing the screenshots in Fig. 7.4, one can see that the position of the horizontal stabilizer could indicate the pitch angle — if the view is augmented with an appropriate scale.

While these approaches might improve the pilots' attitude awareness, they may also unnecessarily draw their attention away from the environment towards the symbology. Thus, it might be better to enhance the view itself

[12] A pilot sitting inside the cockpit has a so-called inside-out view: The aircraft structure remains fixed with regard to the pilot's view. It is the outside world that moves. The PFDs of the majority of (western) aircraft follow the same design principle: The aircraft symbol remains at the same screen position; the artificial horizon moves [245]. Nevertheless, outside-in PFDs have been shown to be superior by several researchers [245, 257].

to include more (unconsciously usable) visual cues. Following this idea, one should challenge the author's decision to not couple the camera frame to aircraft roll & pitch and compare different setups in a pilot-in-the-loop study. One option in this work could be the adoption of the dynamic tether proposed by Colquhoun and Milgram [33] (see Sec. 2.4.3 for details).

Does the exocentric viewpoint also work when actually sitting inside a moving helicopter? Humans integrate the information from their visual and their vestibular system to determine their orientation and motion in space. An immersive HMD is able to disconnect the wearer's real and virtual posture and movement. For instance, a VR user might sit on a desk chair while virtually riding a roller coaster. In such a case, the real pose generates the vestibular stimulus (no motion in this example), whereas the scenario on the VR goggles dictates the visual cues (fast motion and accelerations in the roller coaster). Depending on the scenario and the individual user, this can be fine. However, receiving contradicting information from the two sensory systems can also lead to illusions. Even worse, sensory mismatch is the most common theory to explain simulator sickness or cybersickness [253].

Sitting inside a cockpit of a flying helicopter while seeing the situation from an exocentric viewpoint behind the ownship may cause similar conflicting sensations. The pilot's vestibular system will receive the usual egocentric cues. However, the eyes will not see the matching picture, which would be the standard cockpit view. Instead, the pilot is visually immersed in the tethered view, which is also connected to the translational helicopter movements but certainly delivers different rotational cues.

The effects of this sensory mismatch cannot be predicted without further research. In the present study, no occurrences of cybersickness were observed even though it also induced contradicting sensations (no motion sensed by the vestibular system, but distinct visual motion cues, especially in the cockpit views). Further, the success of fixed-base simulators shows that such constellations still work for many people (at least for a defined time). Finally, another finding that might help is that visual cues are known to be the most important, being even able to override contradicting vestibular sensations in certain scenarios [4].

In conclusion — as the exact causes of cybersickness are not fully understood [253] and the impact is hardly predictable for the given case — it is advisable to conduct further research with the immersive tethered views in a motion simulator and in actual flight tests. If these experiments reveal cybersickness issues, one should also investigate if techniques like dynamic FOV restriction can mitigate the symptoms (see Sec. 3.3.3).

How can the transparent cockpit view be improved? The exocentric viewpoint was found to provide several advantages over the cockpit views. Nevertheless, one should also further research the potentials of a transparent cockpit view. This would have the plus of an eye point that the pilots are used to, well-known and salient motion cues, and lower data source requirements. The questionnaires revealed that the present conformal symbology was less helpful in the cockpit view than in the tethered view. Thus, future work should start by developing a symbology tailor-made for this view type. Moreover, one must take a deeper look at the relation between attitude cues and certain aircraft structures. Knowing which elements are important visual references would enable the display designer to decide which parts of the aircraft structures must be rendered and which can be made semi-transparent or omitted entirely.

7.5 Recapitulation

This chapter explored how a fully virtual cockpit can overcome the restricted out-the-window view and improve the spatial awareness of helicopter pilots operating in confined areas. To do so, two advanced 3-D perspective view types were developed for the immersive HMD:

1. A tethered view that combines the advantages of an exocentric viewpoint (global awareness) with the qualities of an egocentric frame of reference (control and local guidance).
2. A virtual cockpit view that renders the aircraft structures semi-transparent — which allows better outside vision while keeping the familiar cockpit viewpoint.

Both implementations put several potentials of a virtual cockpit into practice. Their major difference to conventional vision systems is that they neither augment (AR-HMD) nor supplement (PMD) the degraded natural view. Instead, they create a completely computer-generated view with the goal to show the world in such a way that pilots can optimally operate in it. The main advantage over PMD-based vision displays is that a VR-HMD creates a rather wide, full-color stereo view, which is real-world-aligned and in which the pilot can naturally look around.

These assumed benefits were confirmed by a pilot-in-the-loop study in the XR-Sim. It yielded the following key findings:

- positive pilot feedback on the overall concept
- tethered immersive view improved the pilots' spatial awareness in confined areas, which led to more precise hover maneuvers and improved obstacle clearance
- significantly reduced head-motion with the tethered view (potential workload & fatigue reduction)
- slight tendency to command larger pitch angles and pilot feedback suggest more complicated helicopter attitude perception with all developed views
- transparent cockpit view requires further development before its actual value can be assessed

In summary, the simulator experiment shows the great potential of a fully virtual cockpit and in particular of tethered views displayed on an immersive HMD. Nevertheless, further work is required to solve the discovered issues (e.g. complicated attitude perception). Finally, the influence of the motion cues when sitting in a flying helicopter has to be explored before a more substantiated review of the concept can take place.

Chapter 8

Conclusions & Future Directions

The following section briefly[1] summarizes the activities and achievements of the dissertation. Thereafter, Sec. 8.2 draws conclusions from the conducted research and Sec. 8.3 makes recommendations for future work.

8.1 Recapitulation

Degraded outside vision — through adverse environmental conditions, aircraft-induced, or operation-specific (see Fig. 1.1) — poses a major challenge for helicopter pilots, especially during operations close to the ground and obstacles. Motivated by the recent technological advancements of head-worn displays, the goal of this dissertation was to explore how such modern HMDs can overcome the limitations of existing display solutions and thereby improve the pilots' situation awareness and increase flight safety. What sets this work apart is that the author explicitly considered non-see-through VR-HMDs besides the established optical see-through devices.

Figure 8.1 provides an overview of the conducted work. It comprised four stages that align with the author's research questions posed in Sec. 1.3.2: 1) concept development to answer RQ 1-A, 2) theoretical assessment (RQ 1-B), 3) practical implementation (RQ 2-A), and 4) experimental evaluation (RQ 2-B).

[1] For more complete descriptions, the reader is advised to refer back to the recapitulation sections at the end of each chapter.

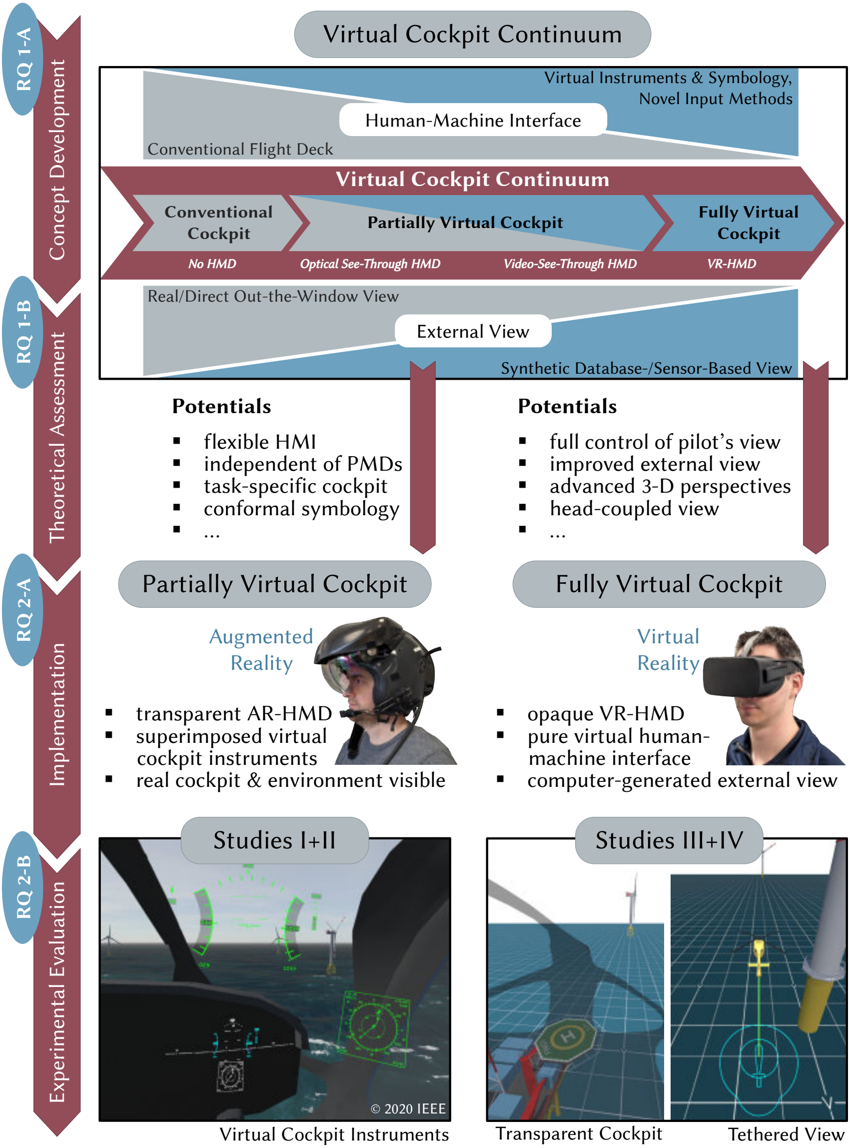


Figure 8.1 – The dissertation in a nutshell — In the initial concept phase the author developed the virtual cockpit continuum and analyzed the potentials and challenges of such an approach. Based on this theoretical framework, he implemented a partially and a fully virtual cockpit and evaluated these in four pilot-in-the-loop studies.

Concept Development The initial phase included a thorough review of existing solutions and resulted in a concept called *virtual cockpit*. The approach builds on state-of-the-art DVE mitigation systems and their established data acquisition via aircraft-mounted sensors and databases. The visual display options, however, are significantly enhanced by new HMD solutions. To reflect these new possibilities, the author devised the depicted *virtual cockpit continuum* — a conceptual framework that defines different variations of a virtual cockpit.

A partially virtual cockpit applies a transparent or video-see-through HMD to augment the out-the-window view with a database-/sensor-based view of the environment. Further, the conventional flight deck is enhanced with virtual instruments & symbology. The farther right in the continuum, the more important become these virtual elements. The fully virtual cockpit at the right pole of the continuum has no physical instrument panel but a pure virtual interface generated by a VR-HMD. Also, the direct view of the surroundings through the cockpit windows is replaced by a computer-generated HMD view, which is made of pre-stored and live-sensed data.

Theoretical Assessment The author's theoretical assessment found several potentials of a virtual cockpit compared to state-of-the-art solutions. A partially virtual cockpit enables the creation of a flexible, task-adaptive HMI with virtual instruments that can be placed independent of the position, size, and availability of conventional PMDs. A fully virtual cockpit even increases this flexibility as the display designer gets full control of what the pilot sees. This can be used to create a virtual world that perfectly fits the pilot's needs: for instance, a real-world-aligned, unobstructed, wide-angle view of the external scene with tailor-made visual cues — or an advanced 3-D perspective view, in which the pilot can intuitively look around by turning the head. By design, immersive HMDs add further advantages like wide display field of view, sophisticated depth cueing, blocking of adverse real-world influences, and higher tolerance for misalignment and latency issues.

On the other hand, the work also detected several challenges to be met before a virtual cockpit can be realized. Most importantly, the novel display solutions require reliable data sources that can provide all relevant information about the surroundings. Another major challenge is the development of suitable methods to interact with such a virtual cockpit. The current limitations regarding display properties (e.g. resolution, FOV) and ergonomics (e.g. weight, balance, wearing comfort) will probably disappear as the technology advances, whereas cybersickness issues certainly require further research. If all other problems are solved, the final question will be how this complex system can be certified and if the benefits can outweigh the costs.

Implementation & Experimental Evaluation The compiled list of potentials and challenges is rather abstract. Thus, it was the goal of the second part of the dissertation to put the conceptual framework into practice and to evaluate concrete virtual cockpit implementations. To do so, helicopter operations in offshore wind farms were chosen as an application scenario because such missions usually involve typical DVE issues like degraded or missing outside visual cues and restricted view of nearby obstructions. To make these practical developments possible, the author built up the XR-Sim — a prototyping and evaluation environment for novel HMDs, which can be connected to DLR's existing simulation infrastructure.

As can be seen from Fig. 8.1, the practical phase had two distinct threads, which focused on different sections of the author's virtual cockpit continuum: 1) the implementation of a partially virtually cockpit with a transparent AR-HMD (left side), and 2) the development of a fully virtual cockpit with an opaque VR-HMD (right).

The former part dealt with the development of virtual cockpit instruments (VCIs), which are essentially 2-D virtual screens projected into the pilot's view by the HMD. This enables a flexible information presentation independent of PMDs. The two conducted simulator studies confirmed the advantages of such a VCI, which showed a top-view obstacle awareness display in this case. The VCI approach in general received high subjective ratings. Further, the head-coupled mode — where the VCI remained inside the pilot's view independent of the viewing direction — generated a safety benefit because it increased the "head-up, eyes-out" time during confined area operations. Consequently, the VCI was preferred by the pilots over the conventional PMD-based obstacle awareness display.

A fully virtual cockpit can have various forms. Here, the author developed a cockpit view with semi-transparent aircraft structures and a tethered view where the pilot sees the ownship from an exocentric viewpoint. The goal of both approaches is to improve the pilot's view of nearby obstacles that are hardly visible from a conventional flight deck. The evaluations confirmed the assumed benefits of the tethered view compared to a conventional cockpit view on the VR-HMD: It increased the pilots' situation awareness in confined areas, which led to more precise hover maneuvers and improved obstacle clearance. Further, it significantly reduced the head-motion in a simulated hover task next to an offshore wind turbine; this may have positive effects on fatigue and workload. Despite these affirmative results, the author also found that the attitude perception seems more complicated with the novel view variants and that the transparent cockpit view requires further advancements. Finally, the influence of motion cues should be investigated in detail.

Summary In summary, the dissertation devised a conceptual framework for a virtual cockpit and identified its potentials and challenges in comparison with the established approaches. Based on this theoretical assessment, the author implemented two distinct virtual cockpit variants and confirmed the practical relevance of the assumed potentials with four pilot-in-the-loop studies. Besides the experimental evaluations, the developed concept and the XR-Sim were presented at the two leading international aerospace exhibitions *Paris Air Show* and *ILA Berlin*. Moreover, the devised VCI found its way into the LuFo project HeliPAS-OW, where it was further developed and flight-tested [181].

8.2 Conclusions

Great Potential, But More Research Required The theoretical assessment and the first exploratory studies confirmed the great potential of the envisioned virtual cockpit. A partially virtual cockpit, as implemented with the VCIs in study I & II, can significantly enhance the conventional HMI. Being already tested on flight-certified hardware, it could be realized in the foreseeable future. According to current regulations, it could, however, only serve as situation awareness aid but not generate operational benefits. Moreover, the experimental evaluations of a fully virtual cockpit clearly showed the benefits of using a non-see-through VR-HMD as principal flight guidance display in DVE scenarios. However, the work also showed that the complete realization of a virtual cockpit requires considerable research, development, and implementation efforts. Thus, the author provides a rather long list of recommendations for future work in the following Sec. 8.3. In the author's opinion, the first results clearly indicate that it is worth putting further effort into the research and development of this idea.

No One-Size-Fits-All Solution A virtual cockpit is not a one-size-fits-all solution. First — as this dissertation already showed — there is no single virtual cockpit for all scenarios. For certain tasks, a "simple" virtualization of only a single instrument, like the obstacle awareness display in study I & II, can generate a major benefit. In other cases, a fully virtual approach may be the best solution. Second, it must be clearly stated that the actual benefit of a virtual cockpit is very task-specific. For many scenarios, a conventional cockpit is *currently* the better choice. Even for many restricted out-the-window view tasks, it may be preferable to equip the helicopter with external mirrors or to open the door during touchdown instead of installing a complex vision system. Nevertheless — if applied in the right way and for the right task — a virtual cockpit can be a solution that enables operations that are not safely possible with today's conventional approaches. Also, requirements like better protection or improved aerodynamics may be an argument for a virtual cockpit without windows. Finally, it is important to note that one is *not* required to use a virtual cockpit for the *entire* flight. In the author's opinion, the first implementations will be "part-time" virtual cockpits where the pilots operate in a conventional flight deck during certain flight phases; and in other phases, they put on the HMD to work in a fully or partially virtual cockpit.

Virtual Cockpit & Automation Even though current research successfully works on highly automated or even autonomous helicopters [298], it is predictable that fully autonomous operations under all possible conditions and for all unforeseen situations will not be realized in the short or medium term. Nevertheless, the role of the pilot will change as tasks that were formerly conducted by the pilot are more and more performed by the automation. However, as long as the aircraft does not fly autonomously, the pilot will still be in command and be responsible for taking important, complex, and heuristic decisions. Depending on the automation level [5], the pilot must also take over manual control in certain situations. This inevitably means that the pilot requires situation awareness. Even if a decision is made by the automation, it is still important that the pilot understands the situation and the actions performed by the machine ("explainable AI"). Otherwise, the pilot will not be "in the loop" to make a decision when required.

In the author's opinion, a virtual cockpit is a good match for such human-centered automation. The work on 3-D perspective views has shown that an exocentric VR view can better support situation awareness than the conventional view from the cockpit. It will, however, only be safe if the helicopter stabilization and control task is sufficiently assisted or automated (see the identified attitude perception issues). With a higher automation level, the display designer can focus more on global awareness than on local guidance and thereby fully use the capabilities and opportunities of an immersive HMD view. For instance, one could enable the pilot to interactively change the viewpoint to assess the situation from various angles. Such an advanced view can also include tactical and strategical information supporting the pilot's new role as tactician and mission commander. An immersive tactical situation display can be especially relevant for manned-unmanned teams, where a manned aircraft commands escorting UAVs to accomplish a mission (cf. efforts by the U. S. Army [301] and the University of the Bundeswehr Munich [104] as well as the European FCAS [66]).

New Technologies Enabling Advanced Virtual Cockpits As the capabilities of HMDs and other required systems have changed during the short time frame of this dissertation project, the technologies will further evolve and novel implementations of a virtual cockpit will be possible. The work was started with Oculus' first development kit — a simple HMD made of a mobile phone display and two low-cost plastic lenses. A few years later, at the end of this dissertation project, the author will continue his work with the highly sophisticated Varjo XR-3, a video-see-through HMD with "human-eye resolution" and the capability to actually fuse stereo video imagery of the reality with virtual content [319]. This will open up a whole new space for future virtual cockpit realizations.

In the medium term — when the technology is mature enough — video-see-through devices may have the potential to replace the common transparent HMDs inside conventional cockpits. This way, one could get the advantages of immersive HMDs (occlusion, no adverse real-world influences, etc.) without the need to drastically change the flight deck and the procedures: Most importantly, no complex new interaction methods will be required if the pilots see their hands and the conventional HMI via the HMD-mounted cameras. The established head-up symbology concepts from see-through HMDs could be used as is. Compared to the changes needed for more radical virtual solutions, this would be a rather small system adaptation.

Overall, future technology advancements will enable the creation of better virtual cockpits. In the long term, this could mean that the author has to revise or revoke his above statement, which says that "for many scenarios, a conventional cockpit is *currently* the better choice". If the pace of the current technological evolution is kept up, an HMD-based virtual cockpit could become a potential candidate to replace conventional flight decks. The author believes that not a fully virtual cockpit but a video-see-through solution with selective/task-adapted combination of real and virtual environment is the most promising approach in this regard.

8.3 Recommendations for Future Work

Application to Other Scenarios This work applied the virtual cockpit concept to specific helicopter offshore operations. However, this does not mean that the developed approaches are only relevant for that specific scenarios. As described in Chapter 1, maneuvers with degraded vision and close-by obstacles are very common for many types of helicopter operations.

For instance, the VCI-OAWD provides a complementary top view without drawing the pilot's attention to a panel display inside the cockpit. This is also relevant in other confined area operations: Off-airfield landings at unprepared sites seem to be an interesting scenario where such a solution could also aid the pilot's spatial awareness. Moreover, the VCI-OAWD is not the only possible implementation of the VCI concept. Thus, it will be interesting for future studies to explore other scenarios where VCIs can generate benefits. A first step is taken by the project HeliPAS-OW where DLR is currently investigating the value of a VCI-based map display in flight trials together with Hensoldt and Airbus Helicopters [181].

Similarly, the benefits of a fully virtual external view were demonstrated with a synthetic ocean surface representation. Follow-up studies should build on these findings and devise a synthetic external scene representation for onshore scenarios. For this work, many concepts from the state-of-the-art vision systems presented in Sec. 2.2 can be transferred to the VR-HMD.

Moreover, flexible cockpit instruments and advanced HMD-based external views seem also relevant for the fixed-wing domain. Potential use cases range from windowless supersonic airplanes via military fighters with little space for PMDs to armored aircraft with restricted external vision. Finally, a fully virtual cockpit does not need to be on board. Its wide-angle, head-coupled view may also make it a superior remote piloting solution.

Further Development of the Fully Virtual External View The work on the synthetic ocean surface representation demonstrated how a fully computer-generated external view can integrate important information in a sensible way. Despite all positive feedback, the author recommends that future work should further investigate the egomotion perception within such VR environments. At the current stage, the preferred abstract ocean surface representations include a limited number of cue-providing elements: a clearly visible horizon and a conformal grid serving as macrotexture, as well as a low degree of microtexture via the dark blue background texture. In the tested scenario, this appeared to be enough to perceive the own drift motion and to align the aircraft with the wind direction. However, as the poor ground speed perception already indicated, the offered cues may not be sufficient for other tasks. Related work shows, for instance, that microtextures are important for hover and low-speed maneuvering [130]. Thus, future work should test different microtexture backgrounds and evaluate if the synthetic cues are sufficient for complex control tasks like hovering.

To advance the fully virtual external view, one should also continue working on the 3-D perspective views, which delivered such promising results in study IV. Section 7.4.2 provides an in-depth discussion on open questions and possible advancements. This includes the investigation of the pilot's attitude perception in exocentric views as well as the influence of motion cues.

Finally, additional flight guidance and navigation information must be integrated into the devised external views. To do so, one should follow the established concepts and visualize waypoints, the desired flight path, and additional indications in a conformal or scene-linked way (see Sec. 2.3).

Advancement to a Holistic Cockpit Concept To explore the potentials of a virtual cockpit, this dissertation focused on the development and evaluation of selected symbology concepts. As this research revealed positive results, the current approach should be expanded to a holistic cockpit concept. One of the next steps on this road will be to enable the pilots to interact with the virtual cockpit environment. The users should be able to adapt the VCI and choose options like they do with conventional instruments. Further, it should be possible to interactively choose between a number of VCI setups depending on the situation and personal preferences. The author already started this development with his work on a "drag & drop mechanism" for VCIs [67]. Recently, this was further advanced [181]. In the author's opinion, the development of intuitive interaction mechanisms is a crucial building block for a successful implementation of a holistic virtual cockpit. Section 3.3.2 outlines several technologies available for that undertaking.

Multi-Modal Information Presentation In light of visual channel overload and HMD clutter, future research should also compare the visual information presentation to haptic and spatial auditory displays. As discussed in Sec. 5.4.1, related work supports the hypothesis that a multi-modal cueing system can enhance the situation awareness, especially for complex scenarios close to multiple obstacles. To investigate if these results can be transferred to a virtual cockpit, the author and his colleagues started the integration of the presented exocentric view with DLR's spatial audio engine SPAACE [223]. A first simulator study in the XR-Sim found a potential benefit of this combination which should be further investigated [22].

Exploration of Video-See-Through HMDs The recent introduction of a new generation of video-see-through HMDs allows a selective and task-adapted visual fusion of virtual and video-streamed real environment (see Sec. 2.1.2.3). This appears to be a very interesting technology because such a device can easily and instantly change the degree of cockpit virtuality. In one situation, the pilot may see a video stream of the real world enhanced with virtual elements, while for another task, the video-see-through mode may be switched off to make the pilot operate with a fully virtual exocentric view.

Such devices were not available during this dissertation. However, recently, with the advent of the Varjo XR-HMDs [319], this technology became widely available. This should be used to further explore its capabilities in the context of a virtual cockpit.

Extension of the Evaluation Methodology Future research should not only enhance the virtual cockpit itself but also extend the evaluation methodology. To do so, the author and his colleagues are pursuing the build-up of a motion platform for the XR-Sim [167] (see Fig. 8.2a). Furthermore, they continue with the integration of an immersive HMD into DLR's research helicopter FHS (Fig. 8.2b) for actual in-flight testing of the simulator-proven concepts. As discussed in Sec. 7.4.2, a motion-based evaluation is needed to further assess the feasibility of an immersive exocentric view when the pilots sit inside the aircraft and move in a different frame of reference. A flight campaign is, for instance, required to reassert the promising results of the VCI evaluation, which were so far obtained on state-of-the-art avionics

(a) Motion platform during the setup and integration process for the XR-Sim.

(b) DLR's research helicopter FHS on which flights tests of a virtual cockpit are planned [r].

Figure 8.2 – Next evaluation steps with motion platform and flight trials.

components in a high-fidelity simulator (technology readiness level 5/6; see Chapter 5). One important test point will be to confirm that the positive feedback regarding clutter and VCI readability holds true for actual in-flight conditions (vibrations, more complicated lighting conditions, etc.).

The conducted work on a fully virtual cockpit focused on exploring various potential symbologies and determining the most promising thereof. After finding that, it should now be the next step to perform an in-depth comparison with state-of-the-art approaches. For the partially virtual VCI solution, this comparison with a conventional cockpit was already successfully performed in study II.

While in an early design stage it is often better to focus on individual pilot feedback and general observations, the next iterations should extend the statistical analysis; this necessarily means to include more study participants.

User-Centered Advancement of HMD Technology In the author's view, it will be important to further develop current HMD technology by following a user-centered approach. On the one hand, this implies that the HMD capabilities must be enhanced to better reflect the capabilities of the human visual system (resolution, field of view, depth cues). On the other hand, this means that one should focus on making HMDs more comfortable for long-time usage and figure out how cybersickness issues can be mitigated.

Data Sources The creation of a virtual out-the-window view requires advanced and reliable data sources. At the moment, no sensor system can provide all data required by an ultimate, all-embracing fully virtual cockpit in all possible scenarios (various flight phases, missions, environmental conditions, et cetera). However, the author's literature review (Sec. 2.2) shows that various sensor solutions for specific scenarios are already available or actively developed. For instance, landing a helicopter in brownout conditions with only a fused sensor/database view on the PMD[2] has been successfully demonstrated [294].

As the focus of this dissertation was on display concepts, the author only listed the required data inputs for each symbology variant (Sec. 5.1.5, 6.1.4 and 7.1.5); the actual integration and fusion of sensor and database data remains for future work. Thereby, it must also be investigated to which degree the current systems satisfy the requirements of each specific type of virtual cockpit and where further advancements are required. The long development times of the involved systems (display & data source) make it reasonable to investigate both technologies in parallel. It is even worthwhile to examine display concepts that will only be realizable with future generations of sensors and data fusion algorithms; otherwise, the new sensor technologies will be available someday but the new symbologies will not. Recent research achievements give rise to optimism that the technology will reach the desired capabilities in the future.

Certification & Economic Viability When all open questions and technical issues are solved, the developed solutions have to demonstrate their reliability in a certification process. The discussion of a path to certification for the developed VCIs in Sec. 5.4.2 has shown that — for such a partially virtual cockpit — this goal may be closer than one might think. The required modules themselves (HMD, sensors, etc.) are already flight-certified and available. For more virtual solutions with HMDs other than the already fielded see-through devices, this process will certainly be longer. Finally, the question will be if operational benefits and increased safety can outweigh the high system complexity and the costs of a virtual cockpit. The author assumes that initial solutions will only target specific scenarios; these can be expanded once the approach has proven its worth.

[2] The cockpit windows were completely masked in these flight trials.

Prior Publications, Presentations & Exhibitions

Parts of this thesis have already been published by the author in several journal articles and conference papers. These publications are listed in the following, together with a list of exhibitions at which the author presented the developed virtual cockpit simulator. Finally, the student theses supervised during this dissertation are specified. Parts taken from the listed publications are marked by footnotes throughout the thesis.

Journal Articles

1. Johannes M. Ernst, Lars Ebrecht, and Bernd Korn. 2021. Virtual cockpit instruments – How head-worn displays can enhance the obstacle awareness of helicopter pilots. *IEEE Aerospace and Electronic Systems Magazine* 36, 4 (Apr. 2021).
2. Johannes M. Ernst, Niklas Peinecke, Lars Ebrecht, Sven Schmerwitz, and Hans-Ullrich Döhler. 2019. Virtual cockpit: an immersive head-worn display as human-machine interface for helicopter operations. *Optical Engineering* 58, 5 (May 2019).
3. Sven Schmerwitz, Thomas Lüken, Hans-Ullrich Döhler, Niklas Peinecke, Johannes M. Ernst, and David L. da Silva Rosa. 2017. Conformal displays: human factor analysis of innovative landing aids. *Optical Engineering* 56, 5 (May 2017).

Scopus Indexed Conference Papers

1. Johannes M. Ernst and Lars Ebrecht. 2020. Virtual cockpit instruments on head-worn displays for helicopter offshore operations in confined areas. In *Proceedings of the 39th IEEE/AIAA Digital Avionics Systems Conference (DASC).*

2. Johannes M. Ernst, Lars Ebrecht, and Sven Schmerwitz. 2019. Virtual cockpit instruments displayed on head-worn displays — Capabilities for future cockpit design. In *Proceedings of the 38th IEEE/AIAA Digital Avionics Systems Conference (DASC).*
3. Johannes M. Ernst, Lars Ebrecht, and Sven Schmerwitz. 2019. Virtual reality headsets as external vision displays for helicopter operations: The potential of an exocentric viewpoint. In *Proceedings of SPIE 11019, Situation Awareness in Degraded Environments.*
4. Johannes M. Ernst. 2018. 3D perspective views on immersive head-worn displays — Can exocentric views increase pilot situational awareness? In *Proceedings of the 31st Congress of the International Council of the Aeronautical Sciences (ICAS).*
5. Johannes M. Ernst, Lars Ebrecht, and Stefan Erdmann. 2018. Synthetic vision on a head-worn display supporting helicopter offshore operations. In *Proceedings of SPIE 10642, Degraded Environments: Sensing, Processing, and Display.*
6. Johannes M. Ernst, Sven Schmerwitz, Thomas Lüken, and Lars Ebrecht. 2017. Designing a virtual cockpit for helicopter offshore operations. In *Proceedings of SPIE 10197, Degraded Environments: Sensing, Processing, and Display.*
7. Johannes M. Ernst, Hans-Ullrich Döhler, and Sven Schmerwitz. 2016. A concept for a virtual flight deck shown on an HMD. In *Proceedings of SPIE 9839, Degraded Visual Environments: Enhanced, Synthetic, and External Vision Solutions.*
8. Lars Ebrecht, Johannes M. Ernst, and Sven Schmerwitz. 2020. Virtual cockpit instruments and visual conformal symbology on head-worn displays for helicopter offshore landings. In *Proceedings of the Vertical Flight Society's 76th Annual Forum.*
9. David da Silva Rosa, Johannes M. Ernst, Clark Borst, Marinus M. van Paassen, and Max Mulder. 2020. Effects of grid cell size in altitude control in an augmented reality terrain display. In *Proceedings of the AIAA SciTech 2020 Forum.*
10. Lars Ebrecht, Johannes M. Ernst, Hans-Ullrich Döhler, and Sven Schmerwitz. 2018. Integration of an exocentric orthogonal coplanar 360 degree top view in a head-worn see-through display supporting obstacle awareness for helicopter operations. In *Human Interface and the Management of Information. Information in Applications and Services.*
11. Lars Ebrecht, Johannes M. Ernst, Hans-Ullrich Döhler, and Sven Schmerwitz. 2018. 360-degree top view inside a helmet mounted display providing obstacle awareness for helicopter operations. In *Proceedings of SPIE 10642, Degraded Environments: Sensing, Processing, and Display.*
12. Niklas Peinecke and Johannes M. Ernst. 2018. Integrating legacy ESVS displays

in the Unity game engine. In *Proceedings of SPIE 10642, Degraded Environments: Sensing, Processing, and Display.*

13. Niklas Peinecke and Johannes M. Ernst. 2017. VR and AR environments for virtual cockpit enhancements. In *Proceedings of SPIE 10197, Degraded Environments: Sensing, Processing, and Display.*

International Exhibitions

1. Paris Air Show 2019. Multimodal cockpit simulator – virtual reality helicopter simulator with 3D-audio and active control loading components.
2. Internationale Luft- und Raumfahrtausstellung (ILA) Berlin 2018. Virtual Reality Helikopter-Simulator mit aktiven Steuerkraftkomponenten.

Presentations & Other Publications

1. Johannes M. Ernst and Christian Niermann. 2020. Multimodal Cockpit Simulator, virtuelle Realität trifft auf 3D-Audio. *Angewandte Forschung für Verteidigung und Sicherheit in Deutschland.*
2. Johannes M. Ernst, Sven Schmerwitz, Thomas Lüken, and Lars Ebrecht. 2017. Analysis of helicopter operations in German offshore wind farms. *EUROCAE WG-79 Meeting #23 & RTCA SC213 Meeting #33, Paris.*
3. Lars Ebrecht, Johannes M. Ernst, and Sven Schmerwitz. 2019. Integration und Potentiale virtueller Cockpit-Instrumente in kopfgetragenen Sichtsystemen. *Deutscher Luft- und Raumfahrtkongress.*

Supervised Student Theses & Internships

1. Moritz Böhm. 2020. Analysis of masking effects during typical helicopter missions in a VR-based cockpit and their compensation by 3-D audio technologies. Bachelor’s thesis, TU Berlin.
2. Carolin Schweitzer. 2019. Evaluation eines Konzeptes zur Integration einer virtuellen Zusatzanzeige für Offshore-Helikopteroperationen in ein kopfgetragenes Anzeigesystem. Studienarbeit, TU Braunschweig.

3. David da Silva Rosa. 2019. Rotorcraft terrain awareness – tau-based approach to helicopter display augmentation in visual degradation. Master's thesis, TU Delft.
4. Tim Laudien. 2018. Entwicklung und Validierung von Flugführungsanzeigen basierend auf VR-Technologien. Projektarbeit, TU Dresden.
5. Stefan Erdmann. 2018. Development and evaluation of an augmented display concept for helicopter offshore flights with a virtual cockpit. Master's thesis, TU Braunschweig. (discontinued)
6. Christina Aures. 2017. Research and prototyping of advanced perspective views on VR-HMDs. Internship, University of Tübingen.
7. Alexander Tesch. 2017. Entwicklung einer Interaktionsschnittstelle für ein virtuelles Cockpit. Master's thesis, TU Braunschweig.

The students contributed the following works to this dissertation: Carolin Schweitzer supported the author during the preparation, the execution, and to a small extent the data analysis of study I (Chapter 5). Tim Laudien implemented the head-up primary flight display used in the same study. Stefan Erdmann contributed to the realization of study III (symbology implementation, study execution). Christina Aures assisted as intern in the initial brainstorming and prototype testing of study IV (Chapter 7).

Abbreviations

3-D SART	3-D Situation Awareness Rating Technique
ACAH	Attitude Command, Attitude Hold
AcCAsH	Acceleration Command, Airspeed Hold
ADS-33	Aeronautical Design Standard - 33
AI	Artificial Intelligence
ANOVA	Analysis Of Variance
AR	Augmented Reality
ATPL	Airline Transport Pilot License
AV	Augmented Virtuality
BOSS	Brown-Out Symbology System
CFIT	Controlled Flight Into Terrain
CMOS	Complementary Metal Oxide Semiconductor
ConOps	Concept Of Operations
CPL	Commercial Pilot License
CVS	Combined Vision System
DA/DH	Decision Altitude / Height
DAL	Development Assurance Level
DARPA	Defense Advanced Research Projects Agency
DFOV	Display Field Of View
DLR	German Aerospace Center
DVE	Degraded Visual Environment
DVE-M	Degraded Visual Environment Mitigation
EASA	European Aviation Safety Agency
EFVS	Enhanced Flight Vision System

EUROCAE	European Organisation For Civil Aviation Equipment
EVS	Enhanced Vision System
FAA	Federal Aviation Administration
FCAS	Future Combat Air System
FCS	Flight Control System
FHS	Flying Helicopter Simulator
FOV	Field Of View
GECO	Generic Experimental Cockpit
GFOV	Geometric Field Of View
GPS	Global Positioning System
HEMS	Helicopter Emergency Medical Services
HMD	Head- Or Helmet-Mounted Display
HMI	Human-Machine Interface
HOFO	Helicopter Offshore Operation
HUD	Head-Up Display
I/O	Input / Output
IAP	Instrument Approach Procedure
ICE	Integrated Cueing Environment
IFR	Instrument Flight Rules
IHADSS	Integrated Helmet And Display Sight System
IR	Infrared
LCD	Liquid Crystal Display
LCoS	Liquid Crystal On Silicon
LED	Light-Emitting Diode
lidar	Light Detection And Ranging
LOS	Line Of Sight
MDA	Minimum Descent Altitude
MMW	Millimeter-Wave
MR	Mixed Reality
NASA	National Aeronautics And Space Administration
NIAG	NATO Industrial Advisory Group

OAWD	Obstacle Awareness And Warning Display
OAWS	Obstacle Awareness And Warning System
OLED	Organic Light-Emitting Diode
OPLS	Obstacle Proximity Lidar System
PFD	Primary Flight Display
PMD	Panel-Mounted Display
POI	Point Of Interest
PPL	Private Pilot License
radar	Radio Detection And Ranging
RCDH	Rate Command, Direction Hold
RQ	Research Question (defined in 1.3.2)
RSAS	Rotorstrike Alerting System
RTCA	Radio Technical Commission For Aeronautics
SAR	Search And Rescue
SVS	Synthetic Vision System
TDZE	Touchdown Zone Elevation
TRCPH	Translational Rate Command, Position Hold
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle
UCE	Usable Cue Environment
VCI	Virtual Cockpit Instrument
VCI-OAWD	VCI-Adapted Obstacle Awareness And Warning Display
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
VR	Virtual Reality
VVCHH	Vertical Velocity Command, Height Hold
XR	Generic Term For AR, VR, MR
XR-Sim	XR Simulator
XVS	External Vision System

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[c] "Two Sea Kings HAR3/3A helicopters, sat on the pan at RAF Valley in the early evening fog" by SAC Dave Rose, Jan. 28, 2009, © Crown Copyright. This image is licensed under the terms of the Open Government Licence OGL (https://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/). Available: https://www.defenceimagery.mod.uk/Home/Search?Query=45152354.jpg (visited on Dec. 19, 2021).

[d] "A Sea King MK7, conducted aircraft control over the Dhofar Mountain Range, Southern Oman" by POA Mick Storey, Feb. 28, 2005, © Crown Copyright. This image is licensed under the terms of the Open Government Licence OGL (https://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/). Available: https://www.defenceimagery.mod.uk/Home/Search?Query=45145954.jpg (visited on Dec. 19, 2021).

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[k] "Troopers from 1-227th Aviation, Task Force Attack, depart a CH-47 Chinook during the unit's winter Spur Ride" by Sgt. 1st Class Eric Pahon, Dec. 8, 2011. This image is licensed under CC BY 2.0 (https://creativecommons.org/licenses/by/2.0/). The image was cropped. Available: https://www.flickr.com/photos/soldiersmediacenter/6537480917 (visited on Dec. 19, 2021).

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Curriculum Vitae

Johannes Maria Ernst

[redacted]

Education

10/2012–04/2015 **Technische Universität München**
Aerospace Engineering – Master of Science

- Passed with high distinction (grade point average: 1.0)
- Master's thesis: *Visualization of Traffic Information in Head-Mounted Displays for Helicopter Navigation*

08/2012–01/2014 **KTH Stockholm – TIME Double Degree Exchange**
Vehicle Engineering – Master of Science in Engineering

10/2008–04/2012 **Technische Universität München**
Aerospace Engineering – Bachelor of Science

- Passed with distinction (grade point average: 1.5)
- Bachelor's thesis: *Noise Optimization of Approach Trajectories in Mountainous Areas Using a Gauss Pseudospectral Method*

09/1998–06/2007 **Erasmus-Gymnasium Amberg**
Abitur (grade point average: 1.6)

Work Experience

09/2015 to date **Deutsches Zentrum für Luft- und Raumfahrt**
Research assistant at the *Institute of Flight Guidance*

- Developed virtual/augmented reality displays to support helicopter pilots in degraded visual environment
- Evaluated assistance systems in simulator and flight trials

10/2014–04/2015 **Airbus Defence & Space Friedrichshafen**
Master's thesis *Situational Awareness Systems Engineering*
- Developed a clustering method of ADS-B traffic data
- Implemented a visualization concept of the pre-processed traffic data for see-through helmet-mounted displays

02/2014–08/2014 **Deutsches Zentrum für Luft- und Raumfahrt**
Student research paper at the *Institute of Flight Guidance*
- Designed and implemented virtual cockpit instruments for a helmet-mounted display

Working student at the *Institute of Flight Guidance*
- Evaluated flight simulator tests with MATLAB to assess HMD symbologies for helicopter DVE operations

02/2012–07/2012 **Deutsches Zentrum für Luft- und Raumfahrt**
Internship at the *Institute of Flight Guidance*
- Assisted in the realization of flight simulator tests with several head-up and head-down displays
- Evaluated flight data using MATLAB in view of the suitability of the displays in degraded visual conditions

11/2011–01/2012 **Airbus Operations GmbH Hamburg**
Internship at *A380 Cabin & Cargo Chief Engineering*
- Supported in day-to-day business
- Cooperated actively in several ongoing projects to ensure continuous airworthiness and to meet customer needs

09/2007–05/2008 **Jurawerkstätten Amberg-Sulzbach**
Civilian service in workshop for disabled people

Awards & Scholarships

07/2015 **Fakultätspreis - Bester Studienabschluss 2015**
Issued by *TU München - Fakultät für Maschinenwesen*

02/2014–09/2014 **Deutschlandstipendium**, sponsored by MAN

Skills

Languages German, English, Swedish, Latin, Ancient Greek

IT MS Office, C, C++, C#, Python, R, MATLAB, LaTeX, Unity, Unreal Engine, OpenGL